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Land use change in the river basins of the Great Barrier Reef, 1860 to 2019: A foundation for understanding environmental history across the catchment to reef continuum

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ABSTRACT

Land use in the catchments draining to the Great Barrier Reef lagoon has changed considerably since the introduction of livestock grazing, various crops, mining and urban development. Together these changes have resulted in increased pollutant loads and impaired coastal water quality. This study compiled records to produce annual time-series since 1860 of human population, livestock numbers and agricultural areas at the scale of surface drainage river basins, natural resource management regions and the whole Great Barrier Reef catchment area. Cattle and several crops have experienced progressive expansion interspersed by declines associated with droughts and diseases. Land uses which have experienced all time maxima since the year 2000 include cattle numbers and the areas of sugar cane, bananas and cotton. A Burdekin Basin case study shows that sediment loads initially increased with the introduction of livestock and mining, remained elevated with agricultural development, and declined slightly with the Burdekin Falls Dam construction.

1. Introduction

The Natural Wonder and World Heritage listed Great Barrier Reef (GBR) and its catchment area have a rich cultural, social and economic history. The Reef, in its current form, has existed for the past ~8000 years (Hopley et al., 2007) coinciding when sea-level approached its present position (Lewis et al., 2013a). Indigenous peoples have occupied the adjacent Queensland coastline for at least the past 45,000 years and the offshore islands of the GBR for at least the past 4300 years (Turney et al., 2001; Rowland, 2008). The arrival of Europeans in the GBR catchment area (GBRCA) (from c. 1840 in southern areas to c. 1865 for the northern areas) resulted in changes to land use including agriculture, mining, forestry and urban townships. Consequential changes to the landscape have included tree/shrub clearing and the resulting reduction of the extent of vegetation bioregions (e.g. Kemp et al., 2007; Seabrook et al., 2006, 2007), the application of fertilisers and pesticides across the agricultural and urban land uses, resulting in increases in the loads of suspended sediment, nutrients (nitrogen and phosphorus) and pesticides delivered to the GBR (Kroon et al., 2012; Waterhouse et al., 2012; McCloskey et al., 2017, 2021a, 2021b). These increased loads have been linked to water quality problems in the GBR lagoon including impacts on water clarity largely related to increased sediment loads predominately from grazing lands (Fabricius et al., 2013, 2014, 2016) and effects related to increased nutrients largely related to fertiliser runoff from sugar cane, other crops and urban lands (De'ath and Fabricius, 2010; Waterhouse et al., 2012; Schaffelke et al., 2017). Increased nutrient delivery has also been linked to more frequent Crown of Thorns Starfish outbreaks (Fabricius et al., 2010, but see also Pratchett et al., 2017 who consider other factors). Collectively these water quality pressures influence the condition of coral (De'ath et al., 2012) and seagrass (Petus

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et al., 2014) in the GBR. However, understanding of links between temporal changes in basin land use and the condition of coral reefs, seagrass meadows and other ecosystems of the GBR remains weak, in part due to inaccessible continuous spatial and temporal land use history data. Some studies have documented land use changes for individual basins (e.g. Neil, 1994; Lewis et al., 2007; Kroon et al., 2016; Bartley et al., 2018), bioregions (Seabrook et al., 2006, 2007), and at a high level for the entire GBRCA (e.g. Gilbert and Brodie, 2001; Furnas, 2003). However, there are strong spatial patterns in the timing of land use changes over the 423,000 km^2 area of the GBRCA, and a compilation of land use changes for the individual surface drainage basins (Stein et al., 2011) or for the six Natural Resource Management (NRM) regions (NRM regions, 2017) is lacking. Such a compilation is critical for understanding when considerable changes to the landscape and land use (and associated pollutant loads) occurred, to provide a foundation for examining catchment-to-reef linkages and to compare with biophysical records and environmental/ecological reconstructions.

Previous studies have comprehensively documented the historical harvesting of marine resources in the GBR such as turtles, dugongs, coral and fish (Daley, 2014; Daley and Griggs, 2006, 2008; Daley et al., 2008a, 2008b; Thurstan et al., 2016a, 2016b, 2016c, 2018; Buckley et al., 2017); the mining of guano and phosphate deposits on the islands of the GBR (Daley and Griggs, 2006) and; the dredging history of certain ports (Pringle, 1989). Several manuscripts have documented large-scale tree/shrub clearing and draining of wetlands within the GBRCA (Graetz et al., 1995; Kemp et al., 2007; Russell and Hales, 1993; Furnas, 2003; Great Barrier Reef Marine Park Authority, 2014; Reside et al., 2017) as well as charted the growth of the livestock (cattle and sheep) (Daly, 1983, 1994; Lloyd, 1984; Seabrook et al., 2006, 2007; Lewis et al., 2007; Irvine, 2016; Kroon et al., 2016), wheat (Daly, 1994) and sugar cane (Griggs, 1997, 2007, 2011) industries, but most of these records are now dated and/or restricted to particular areas (whole of Queensland, bioregion) or river basins of the GBRCA. While current (i.e. since 2008) statistical reports specifically report for NRM regions (ABS, 2020a), the historical statistical records are only available in year books and the statistical districts do not always match drainage basins or NRM regions. The beef cattle, sugar cane, grain, horticulture, mining (in particular gold, coal and historically, tin) and tourism industries provide the economic base of many communities within the GBRCA (Fig. 1; Table 1) and this history has its own cultural and social significance (e.g. Fox, 1919-1923; Jones, 1961; Bolton, 1963; Neal, 1984; O'Donnell, 1989; Carpenter, 1991; Kerr, 1994; Megarrity, 1998). Hence charting the major changes to the landscapes of the GBRCA also captures the historical economic changes in the region and provides insights into past management practices.

This study has three broad aims. Firstly, we review the literature describing the climate and vegetation changes in the GBRCA prior to the arrival of Europeans, as context for the more recent land use changes. Secondly, we compile annual human population, livestock (cattle and sheep) and cropping (total crops, other crops including grains, sugar cane, bananas and cotton) land use data at the finest statistical district level within the six NRM regions of the GBRCA: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary (Fig. 1A) from 1860 to 2019. The data are also compiled to construct land use changes for the individual basins within five of the six NRM regions (i.e. Cape York excluded). Our overall aim is to produce a key resource of land use changes in the GBRCA at fine spatial (i.e. basin-scale) and temporal (i.e. annual) resolutions so it may be used to examine long term trends in response to climate and management change and to inform investigations into changes in environmental issues. Due to timing (and manuscript length) constraints, we could not reconstruct time series histories for all major land uses (e.g. mining, forestry etc), although their current extents and distribution in the GBRCA are provided from the Queensland Land Use Mapping Program (QLUMP, 2020) in Fig. 1B and Table 1. However, we have captured the spatially dominant land uses that we consider the most important in terms of contribution to elevated pollutant loads to the GBR (Fig. 1; Table 1; Waterhouse et al., 2012; McCloskey et al., 2017, 2021a, 2021b). We also note that tourism, although economically important, is not considered as a specific land use or explicitly documented in this study. Thirdly, we use the time series of climate and land use data reconstruction from the Burdekin Basin as a case study to demonstrate the value of these data for interpreting environmental histories. The Burdekin Basin covers a vast area (~130,000 km^2), is the largest contributor of discharge and suspended sediment loads to the GBR lagoon, and has been subject to a relatively large body of scientific research that has produced temporally constrained environmental records that allow comparison with our land use time series.

2. Climate and vegetation records as indicators of landscape change before 1860

It is well established that prior to the arrival of Europeans, Aboriginal Australians used fire to modify vegetation type and to maintain open grass lands for hunting (Jones, 1969; Flannery, 1994; Gammage, 2011). Indeed, both fire and natural climate variability have shaped the composition and structure of vegetation on the landscape over millennia, although the relative influence between the two drivers are debated. In that regard, pollen and geochemical records from crater lakes on the Atherton Tablelands of the Wet Tropics NRM region indicate temporal variability in vegetation structure and composition prior to the arrival of Europeans. Sediment cores have been collected from Lake Euramoo, Quincan Crater, Bromfield Swamp, and Lynch's Crater (among others) since the 1970s and the data from these cores remain collectively among the most important terrestrial vegetation and climate records from north Queensland (Reeves et al., 2013). Earlier seminal studies led by Peter Kershaw conducted analyses of pollen grains within the cores, which showed local transitions from eucalypt vegetation (drier climate conditions) to various rainforest species (including warm temperate and subtropical rainforests which indicate wetter conditions), and also evidence for increased fire frequency coinciding with the arrival of Aboriginal Australians (Kershaw, 1970, 1971, 1974, 1975, 1976, 1994). Improved dating techniques (including new methods and better calibration of ages) coupled with the collection of new cores have refined the timing of these vegetation transitions observed in the cores and produced longer climatic records.

The most important site on the Atherton Tablelands, in terms of the production of valuable climate information, is Lynch's Crater. This was formed around 230,000 years ago with an explosive volcanic eruption that created a large depression/lake in the landscape (Rieser and Wust, 2010). This Crater Lake was more than 80 m deep but has since infilled with organic sediments, inorganic materials (e.g. freshwater diatoms and sponges), aeolian dust and erosion of adjacent basin soils. Sediment cores up to 64 m deep have been collected from the ancient lake and both pollen records (Turney et al., 2004; Kershaw et al., 2007; Kershaw, 1994) and geochemical tracing studies (e.g. Muller et al., 2006, 2008a, 2008b; Kylander et al., 2007; Turney et al., 2006) have provided critical insights on climate and environmental variability in north Queensland over the past ~200,000 years. For example, the pollen and charcoal analysis of the sediment cores show that vegetation changed from rainforest to eucalypt and back again repeatedly, indicating that the climate was characterised by cycles of variation between humidity and aridity related to historical changes in El Niño Southern Oscillation regimes, Dansgaard-Oeschger/Heinrich events and orbital forcing (precession). The increased frequency of fire shown by the charcoal records from the Lynch's Crater cores has been dated between 55,000 and 45,000 years BP and is thought to provide a minimum time for the arrival of Aboriginal Australians to the region (Turney et al., 2001; Kershaw et al., 2007). The various geochemical analyses that have been conducted on the sediment cores trace the sources of the different sediments and provide insights on changing erosion rates, atmospheric inputs (from long-distance sources), climate fluctuations (similar climatic

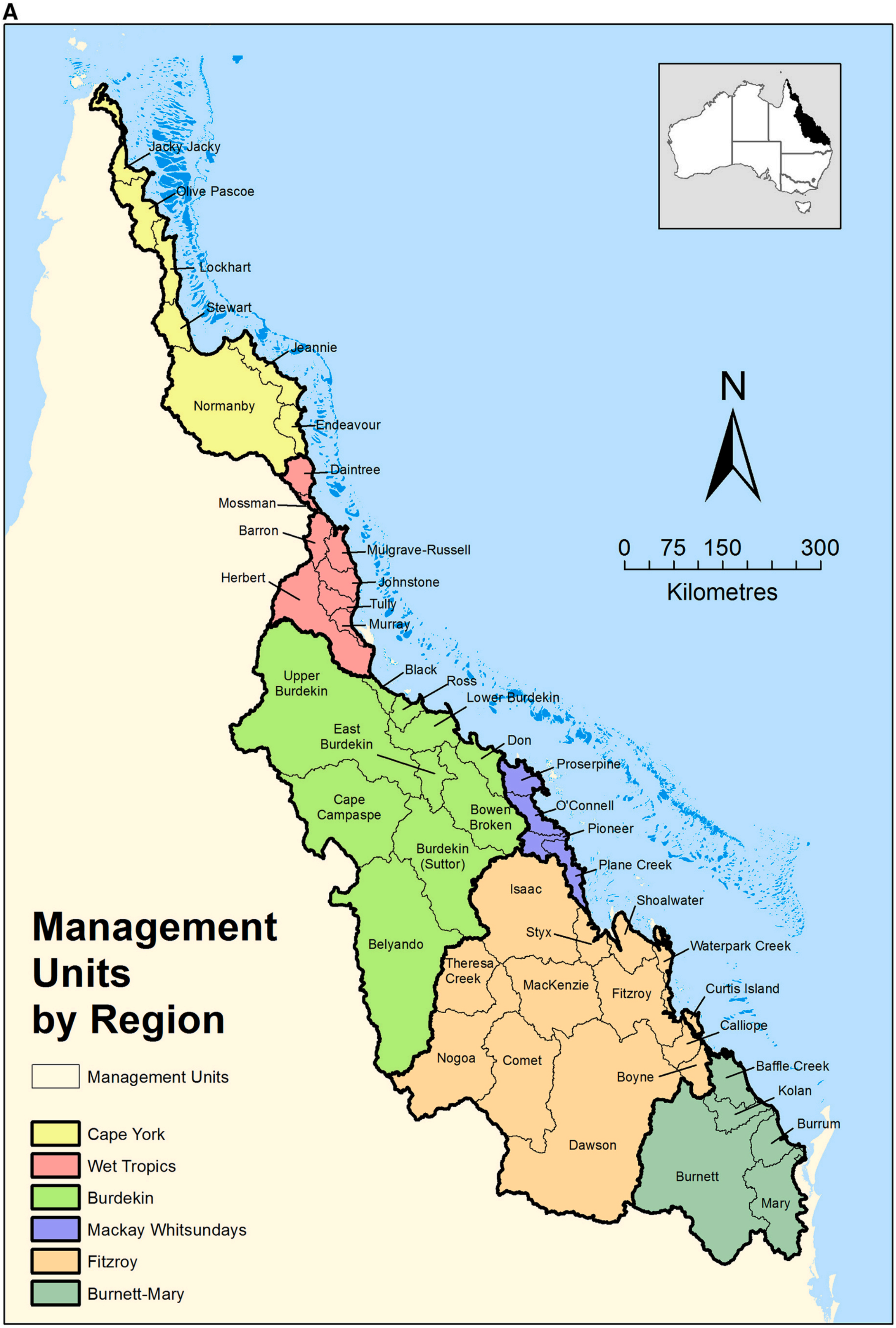
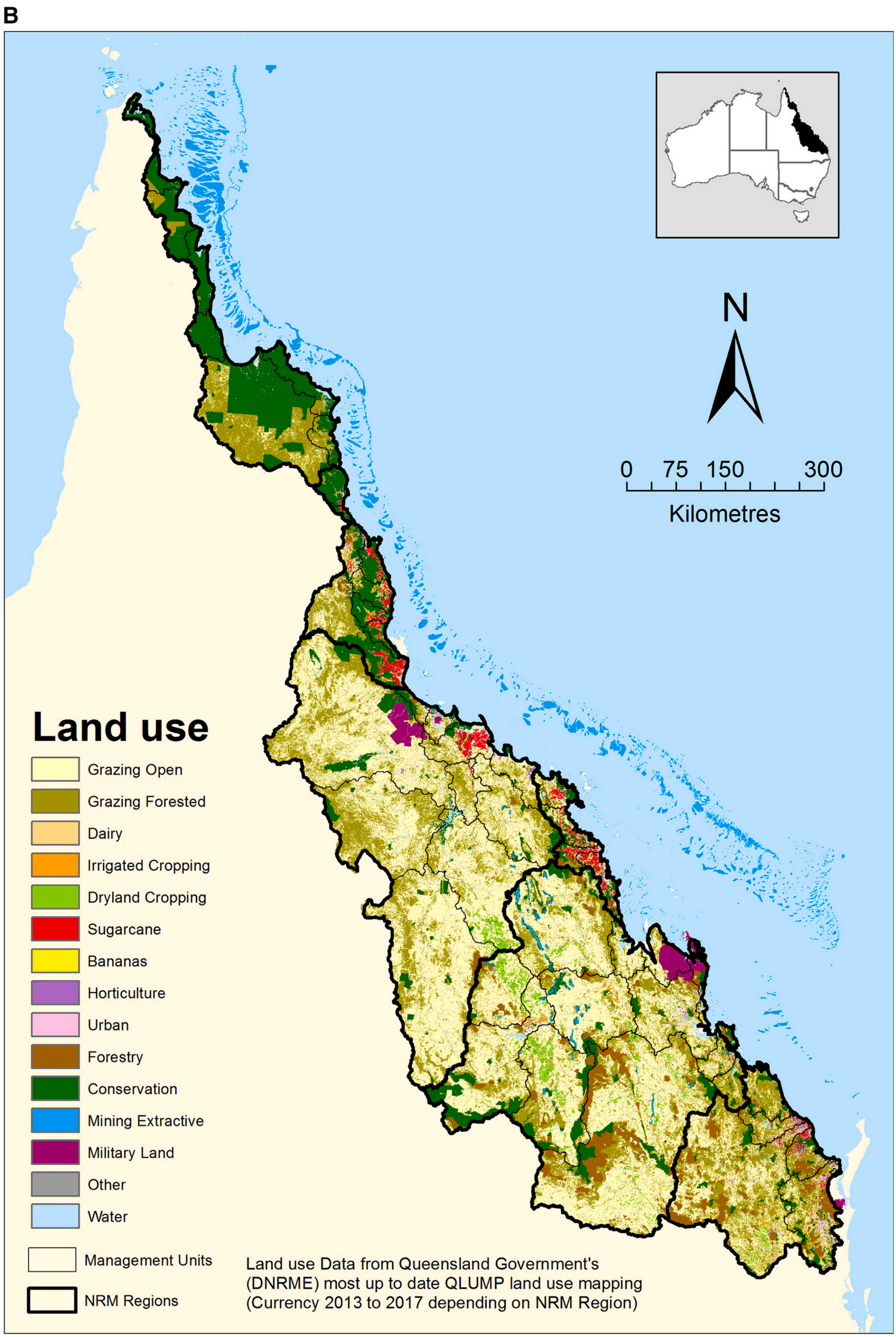


Fig. 1. Map showing the Great Barrier Reef catchment area and the six natural resource management (NRM) regions, river basins and sub-basins (of the Burdekin and Fitzroy Basins) within the area (A) and the key current land uses across the Great Barrier Reef catchment area according to QLUMP (2020) (B).



Land use Data from Queensland Government's (DNRME) most up to date QLUMP land use mapping (Currency 2013 to 2017 depending on NRM Region)

Fig. 1. (*continued*).

Table 1
Summary of the key land uses across the river basins and NRM regions of the GBRCA as reported by QLUMP. The bolded text represent the grouped data at the NRM region and GBRCA scales.

Basin/region	Area (km2)	Grazing area (km2)	Cattle	Dairy	Irrigated cropping	Dryland cropping	Sugarcane	Bananas	Horticulture	Urban	Forestry	Conservation	Mining extractive	Military land	Other	Water
Jacky Jacky Creek	2963	249	8.8%									82%				9.1%
Olive Pascoe River	4180	877	21%									78%				0.3%
Lockhart River	2883	72	2.6%									93%			0.1%	4.6%
Stewart River	2743	68	2.5%									94%				3.8%
Normanby River	24,399	12,873	53%			0.2%						46%				0.9%
Jeannie River	3638	389	11%								0.6%	81%	0.2%			7.0%
Endeavour River	2182	911	44%			0.1%			0.1%	1.3%	0.9%	52%	0.1%		0.3%	1.1%
Cape York NRM	**42,988**	**15,439**	**36%**			**0.1%**				**0.1%**	**0.1%**	**61%**				**2.4%**
Daintree River	2107	185	8.8%				1.8%	0.1%	0.1%	0.8%		86%				2.4%
Mossman River	473	20	4.3%				9.6%		0.2%	4.7%	0.2%	75%	0.2%		2.1%	3.4%
Barron River	2188	689	32%	0.8%	2.7%		4.4%	0.9%	2.4%	6.2%	11%	36%			1.3%	2.8%
Mulgrave-Russell River	1983	85	4.3%	0.5%		0.1%	12%	0.7%	0.2%	3.5%	0.4%	72%			1.1%	5.0%
Johnstone River	2325	537	23%	1.7%	0.1%	0.2%	11%	2.7%	0.2%	2.9%	0.1%	56%			0.6%	1.6%
Tully-Murray River	2790	187	6.7%				14%	2.2%	0.2%	1.1%	3.3%	70%			0.4%	2.3%
Herbert River	9844	5339	55%	0.1%	0.3%		7.8%		0.1%	0.7%	4.1%	28%			0.1%	4.1%
Wet Tropics NRM	**21,710**	**7042**	**33%**	**0.3%**	**0.4%**		**8.4%**	**0.7%**	**0.3%**	**1.9%**	**3.4%**	**48%**			**0.5%**	**3.4%**
Black River	1057	438	39%				1.6%		0.8%	3.0%	7.0%	40%	0.4%	2.8%	1.4%	3.2%
Ross River	1707	823	49%		0.1%				0.5%	8.2%	2.7%	21%	0.4%	5.7%	4.5%	8.3%
Haughton River	4051	2692	55%		0.3%	0.1%	20%		0.9%	0.7%	0.5%	11%	0.1%	1.9%	0.8%	8.6%
Upper Burdekin/Cape	60,668	53,045	89%							0.1%	0.1%	5.9%	0.1%	3.2%	0.1%	1.8%
Belyando/Suttor	35,352	49,137	92%		0.1%	2.3%					0.8%	2.4%	0.1%		0.1%	2.0%
Bowen/Broken/Bogie/ East Burdekin	34,100	13,347	90%		0.1%		0.3%			0.1%	1.2%	6.3%	0.5%		0.1%	1.9%
Burdekin River	**130,120**	115,529	90%		0.1%	1.0%					0.5%	4.5%	0.1%	1.5%	0.1%	1.9%
Don River	3736	2744	83%		0.1%		0.1%		3.0%	0.6%		6.3%	0.1%		0.5%	6.3%
Burdekin NRM	**140,671**	**122,226**	**88%**		**0.1%**	**0.9%**	**0.8%**		**0.1%**	**0.2%**	**0.6%**	**5.2%**	**0.1%**	**1.6%**	**0.2%**	**2.3%**
Proserpine River	2494	1123	46%				10%		0.8%	2.0%	5.6%	27%			1.1%	7.3%
O'Connell River	2387	987	43%		0.1%		14%			2.0%	7.4%	27%			0.7%	6.1%
Pioneer River	1572	387	23%		0.1%		21%			3.2%	18%	29%	0.1%		1.6%	4.0%
Plane Creek	2539	598	24%		0.2%		25%		0.2%	3.6%	6.0%	32%	0.1%		1.4%	7.5%
Mackay Whitsunday NRM	**8992**	**3095**	**35%**		**0.1%**		**17%**		**0.3%**	**2.7%**	**8.4%**	**29%**	**0.1%**		**1.2%**	**6.4%**
Styx River	3013	2351	79%			0.2%	0.3%				1.6%	6.6%			0.5%	12%
Shoalwater Creek	3601	1646	46%								0.2%	0.7%	0.1%	45%	0.1%	7.3%
Water Park Creek	1836	291	17%						0.4%	4.9%	11%	13%		39%	0.7%	15%
Isaac/Connors/ McKenzie	35,354	29,100	82%		0.6%	1.4%				0.1%	2.9%	8.1%	2.5%		0.5%	1.7%
Nogoa/Theresa/Comet	44,959	32,090	71%		1.1%	7.4%			0.1%	0.1%	4.5%	13%	0.4%		0.4%	1.4%
Dawson	50,734	38,745	77%		0.4%	3.1%				0.1%	13%	6.0%	0.2%		0.5%	0.6%
Lower Fitzroy	11,505	9018	80%		0.3%	0.9%			0.2%	1.6%	3.5%	5.5%	0.1%	2.7%	1.3%	3.9%
Fitzroy River	**142,552**	108,953	77%		0.7%	3.8%				0.2%	6.9%	8.8%	0.9%	0.2%	0.5%	1.4%
Calliope River	2241	1684	75%						0.3%	2.1%	6.3%	9.0%	0.4%		2.3%	4.3%
Boyne River	2496	1825	73%		0.1%	0.1%				1.1%	5.7%	15%	0.2%		0.8%	3.8%
Fitzroy NRM	**155,740**	**116,750**	**75%**		**0.6%**	**3.5%**				**0.3%**	**6.6%**	**8.7%**	**0.8%**	**1.7%**	**0.6%**	**2.0%**
Baffle Creek	4085	2699	68%			0.1%	0.1%		0.5%	0.9%	5.1%	21%			0.8%	3.8%
Kolan River	2901	2001	68%		0.1%		3.2%		2.2%	3.1%	8.6%	9.9%			0.5%	4.4%
Burnett River	33,207	25,589	78%		1.0%	1.9%	0.4%		0.4%	0.9%	12%	4.3%	0.1%		0.4%	0.7%
Burrum River	3362	1387	40%		0.3%	0.1%	7.4%		3.1%	5.0%	22%	17%	0.2%		1.5%	2.5%
Mary River	9466	5144	55%		0.3%	0.1%	1.8%		0.5%	6.1%	20%	14%	0.1%		1.1%	0.9%
Burnett Mary NRM	**53,021**	**36,820**	**70%**		**0.7%**	**1.2%**	**1.3%**		**0.7%**	**2.2%**	**14%**	**8.3%**	**0.1%**		**0.6%**	**1.3%**
GBR Total	**423,122**	**301,372**	**72%**		**0.4%**	**1.8%**	**1.0%**		**0.2%**	**0.6%**	**4.7%**	**15%**	**0.3%**	**1.1%**	**0.4%**	**2.2%**

events identified in the pollen information), fluvial response (Hughes and Croke, 2017) and the water levels of the lake. Another key high resolution record is from Lake Euramoo which revealed much drier conditions during the Last Glacial Maximum (~24 to 20 ka); a change from sclerophyll vegetation to the current rainforest dominance by 8 ka; increasing evidence for fire (Aboriginal burning or changing El Niño Southern Oscillation conditions) over the past 7–8 thousand years and; the more recent appearance of exotic species (last ~100 years) associated with arrival of Europeans (Haberle, 2005). Other lake core records within the neighboring Cape York NRM region show similar trends in vegetation changes (e.g. Luly et al., 2006).

An important body of work in the Burdekin NRM region has been developed by Roderick Fensham and colleagues who examined the differences in vegetation composition surrounding the Great Basalt Wall ~50 km NW of the township of Charters Towers. Here the 20 ka Toomba lava flow (Mishra et al., 2019), which formed the Great Basalt Wall, has created ‘pockets’ that exclude cattle but are still accessible by the native macropods. A diversity of dryland rainforest species exists within these pockets which do not occur in the surrounding landscape; the pockets also contain a dominance of perennial grasses in comparison to the current mixture of native/exotic perennial-annual grasses in the surrounding grazed area (Fensham and Skull, 1999). The dryland rainforest species occur within the pockets as clumps that surround large savanna trees and have likely formed due to the dispersal of seeds from birds and bats (Fensham and Butler, 2004). However, the persistence of dryland rainforest species in these pockets, which have been shown to be highly sensitive (in terms of both intensity and frequency) to fires (Fensham et al., 2003), indicates that there is a reduced incidence of fire relative to the broader landscape in this location.

Other insights on pre-European vegetation composition and landscape geomorphology have been provided from historical surveys/maps, photographs, sketches/paintings and the descriptive accounts of the explorers and pioneering Europeans. These documents largely depict vast open plains thickly covered in diverse grasses, and open forests/woodlands also with thick vegetation cover (e.g. Leichhardt, 1847; Flannery, 1994; Fensham, 2008; Gammage, 2011; Thorburn et al., 2013). The descriptions of the hydrology and soils frequently refer to the high soil moisture absorbance with terms such as ‘rotten’ (referring to the bogginess of the soils with horses and cattle sinking into the soil), ‘absorbed the rain rapidly’ and the abundance of waterholes in creeks (Leichhardt, 1847; Thorburn et al., 2013). Large changes in the ecosystems of the GBRCA since the arrival of Europeans (‘pre-clearing’) is evident in the ‘coastal ecosystems’ vegetation mapping conducted by the Great Barrier Reef Marine Park Authority (2014), which depicts large reductions in several ecosystem areas between the pre-European reconstruction and the current extent. The most striking of these changes is the reduction in the extent of Brigalow *Acacia* ecosystems, which were particularly abundant in the central Queensland region prior to the arrival of Europeans (see Skerman, 1959; Lloyd, 1984); across the Fitzroy and southern Burdekin Basins (including Belyando, Jericho, Emerald, Peak Downs, Broadsound, Bauhinia and Duaringa districts), they originally covered an area of 31,700 km^2 prior to 1860 which by 1995 was down to 4820 km^2 (Fensham et al., 1998). Forest cover in the near-coastal zone has also declined markedly (e.g. Griggs, 2007; Kemp et al., 2007). While some broad components of the landscape appear unchanged, in many cases there has clearly been considerable modifications since the arrival of Europeans and the timing of associated land use changes are explored further in this study.

3. Methods

3.1. Spatial units

A key feature of the study was to develop continuous time series spanning multiple historical administrative spatial units and allocate these to drainage basins (river catchments and basins: Stein et al., 2011), and NRM regions (NRM regions, 2017) which are agglomerations of river basins. Historical data were assigned from their originally reported spatial units into the drainage basins or apportioned between two or more drainage basins where the historical unit spanned more than one drainage basin. Interpreting the effect of differences in reporting methods over time was also a feature of the method, as was transferring data from hard copy into digital formats to enable further analysis.

3.2. Population

We obtained the annual estimated resident (human) population (ERP) data for the shires/local government areas from the Australian Bureau of Statistics (ABS, 2020b). These data are updated annually using a model which draws on data such as dwelling approvals, Medicare (i.e. public healthcare) enrolments and electoral enrolments to estimate population change. In census years, the ERP numbers are based on the usual manual counts of residents which also take into account residents who were temporarily absent. Hence the ERP data vary from the data reported in the census, the latter of which reports the total population residing in the local government area during the night of data collection. We note that the ERP estimates are generally lower than the census estimates due to the extra tourists that visit the region during the census period which usually coincides with the peak tourist season (e.g. Gilbert and Brodie, 2001). In addition, Indigenous Australians were not included in the ERP or census until 1961 and so reporting prior to then would have been underestimated. In any case, the ERP dataset is the finest-resolution and best available data on the longer-term changes in population in the GBRCA.

The statistical areas reporting resident population (i.e. shires, local government areas) within the GBRCA have remained relatively stable since 1860, although some name changes, splits or mergers have occurred over time (Fig. 2A to D). One of the larger changes occurred in 2008 when several areas were merged into larger management regions. The data reported for these merged areas extend back to 1991, allowing for a 17 year overlap with the previous dataset (see Supplementary data). Importantly, the overlap in the datasets in 2007 has been used to inform the proportional allocations of the local government area district data to the river basins for the (higher spatial resolution) earlier dataset. A more detailed description of the data analysis methods used to integrate the historical mapping areas can be found in the Supplementary material.

3.3. Agriculture

Consistent and continuous time series of livestock numbers and cropping areas were compiled at the basin, NRM region and GBRCA scales from district-level data from the annual Queensland Statistical yearbooks (Statistics of the Colony of Queensland, 1860–1900; Statistics of the State of Queensland, 1901–1974) and the Australian Bureau of Statistics (ABS) (1975–2019; ABS, 2020a). Broadly, there have been three major periods of district area reporting over the 1860 to 2019 period (see Table 2; Supplementary material; Irvine, 2016). Specifically, the first period involved the reporting of ‘police districts’ (1860–1891) and ‘petty sessions districts’ (1892–1939) (Fig. 3A and B). The second major period involved the reporting of ‘local authority areas’ (1941–1982) and ‘statistical local areas’ (1983–2006) (Fig. 3C) while the third major (and current) period involves the establishment of ‘Statistical Level Areas’ (SA) which was implemented for the 2011 statistics (Fig. 3D) (Table 2). The ABS compile their statistics at the finest scale SA1, although only the SA2 data (i.e. a grouping of select SA1 data into larger areas) are reported publicly due to privacy reasons (ABS, 2020a). We note that the ABS (2020a) has reported agricultural data annually at the NRM region scale since 2008 (i.e. include ‘gap years’ when district-scale data were not reported and hence basin-scale numbers cannot be calculated) and so we have also compiled these data to report at the relevant scales (NRM and GBRCA). We report all

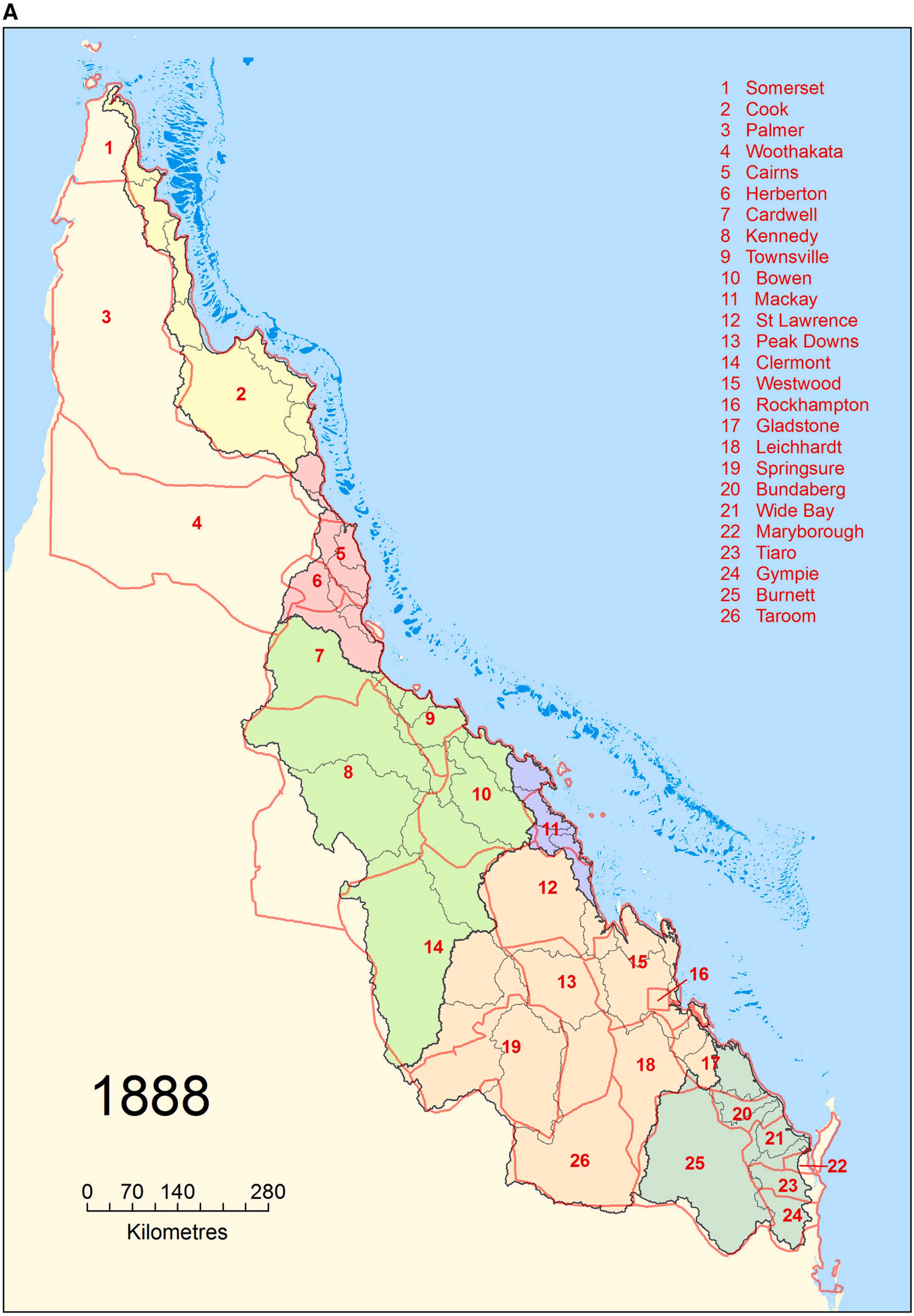

A
1 Somerset
2 Cook
3 Palmer
4 Woothakata
5 Cairns
6 Herberton
7 Cardwell
8 Kennedy
9 Townsville
10 Bowen
11 Mackay
12 St Lawrence
13 Peak Downs
14 Clermont
15 Westwood
16 Rockhampton
17 Gladstone
18 Leichhardt
19 Springsure
20 Bundaberg
21 Wide Bay
22 Maryborough
23 Tiaro
24 Gympie
25 Burnett
26 Taroom
1888
0 70 140 280
Kilometres

Fig. 2. Maps showing the changes in the Shires/Local Government Areas (LGAs) over the past 160 years which were used to report human resident population. The areas are overlain with Natural Resource Management (NRM) Region boundaries and river basins in the Great Barrier Reef catchment area (see Fig. 1). For full page versions of these figures the reader is referred to the Supplementary materials.

statistics to two significant figures throughout the manuscript given the concerns on data accuracy (Daly, 1994; Mortiss, 1995; see also Supplementary materials), although the raw data can be found in the associated Supplementary data. Detailed descriptions on the compilation of the district level statistical data including changes in district areas, the allocation of those data to basin-level scales and the data accuracy and interpretation can be found in the Supplementary material.

3.4. Burdekin Basin case study data compilation

To demonstrate how the land use compilation can be applied to interpret environmental histories, we integrated a range of data sets for the Burdekin Basin to specifically examine the influence of land use and climatic variability on historical sediment loads. The Burdekin Basin was selected as a case study not only due to is size and relative importance to sediment loads to the GBR but also due to the knowledge that sediment loads exported from this basin have changed greatly since the arrival of Europeans with land use changes (general increase in sediment supply) and the construction of the Burdekin Falls Dam (reduction in sediment supply). We acknowledge that other constituents are also problematic for this basin (e.g. dissolved inorganic nutrients and particulate nutrients), however, it was beyond the scope and length of the paper to consider these parameters.

The time series of climate, land use, sediment load and other environmental data to inform the Burdekin Basin case study were compiled from a variety of sources. The daily gridded rainfall data (1890–2018) were downloaded from the Scientific Information for Land Owners (SILO) component of the Long Paddock website (Stone et al., 2019) and processed to produce an annual (water year: 1st October to 30th September) Burdekin Basin rainfall time series following the method of Jarihani et al. (2017). The Burdekin River annual (water year) discharge data (1922–2019) for the Home Hill (120001A: 1922–1950) and Clare (120006A, 120006B: 1951–2018) gauging stations were downloaded from the Department of Natural Resources and Mines (DNRM, 2019) website. To produce a continuous time series for the period 1850–2018, these discharge data were combined with a discharge reconstruction for the period 1850–1921 developed by Lough et al. (2015), who used luminescent lines preserved in *Porites* coral cores from Havannah Island (~ 150 km northwards of the Burdekin River mouth); when a slice from a coral core is placed under ultra violet light, yellow-green lines can be observed, the intensity of which can be measured and directly correlated with river discharge volume from the adjacent catchment (these were first described by Isdale, 1984).

The Burdekin Basin resident human population, cattle and sheep numbers and total area under cropping were compiled using the methods outlined above and in the Supplementary materials. The gold mining time series was compiled from Queensland Department of Mines year books (Queensland Government, 1878-1989) and from the Statistics of the Colony of Queensland (1869–1877) and include the quantity (ounces, oz) of gold sent by escort from the Charters Towers, Cape River and Ravenswood gold fields (1869–1877); the total fine gold yield (oz) recovered from all sources from these fields (1878–1978); and total gold from all sources (including gold bullion) from these fields (1979–1989). These gold metrics are broadly comparable and what we consider the 'best available' time series to capture the gold mining activities across the key Charters Towers, Cape River and Ravenswood goldfields. Early gold mining focused on alluvial and quartz reef diggings and so coupled with periodic floods it directly impacted the sediment supply (Neal, 1984). Unfortunately the recent data sources (1990-current) were not able to be uncovered, although contemporary gold mining of reef deposits would not have had the same impact on river sediment loads due to improved practices (although we note issues such as high acidity and heavy metal runoff still can occasionally occur with tailings overflows during high rainfall events as well as legacy mining issues).

Concentrations of trace elements measured in coral cores (e.g. Manganese, Mn, Barium, Ba and Calcium, Ca) are considered useful for tracking environmental changes (i.e. changing terrestrial inputs such as discharge and sediment loads) from catchments to marine systems (Saha et al., 2016). The coral Mn concentration time series for the Burdekin catchment was taken from Lewis et al. (2007) who measured the geochemistry at biannual resolution from a coral core from Magnetic Island (~ 100 km to the north of the Burdekin River mouth). The annual peak Ba/Ca ratios were extracted from the data of McCulloch et al. (2003) and Lewis et al. (2018) who measured Ba/Ca ratios in coral cores from Havannah Island.

The 'measured' Burdekin sediment loads were derived from a number of different sources including using the suspended sediment concentration data from Belperio (1978, 1979) coupled with DNRM (2019) discharge data to calculate loads for the 1973/74 and 1974/75 water years using the Loads Regression Estimator (LRE) model (Kuhnert et al., 2012). The Burdekin River measured loads for the 1986/87 to 2009/10 water years were reported in Kuhnert et al. (2012) who used the LRE model. Loads covering the financial years (1st July to 30th June) from 2010/11 to 2017/18 were compiled from the annual reports from the Great Barrier Reef Catchment Loads Monitoring Program conducted by the Queensland Department of Environment and Science (Turner et al., 2013; Wallace et al., 2014, 2015, 2016; Garzon-Garcia et al., 2015; Huggins et al., 2017; Ten Napel et al., 2019a, 2019b). We consider that there is little difference between the loads reported for either water year or financial year as both capture the wet season period (November to April) when the vast majority of the sediment load is delivered.

To extend the sediment load record and to facilitate broad comparisons between the basin level statistical data and end of river sediment loads, we provide two separate published model reconstructions produced using two separate methods. The first model is termed 'Reconstruction 1 (agriculture)' which was taken from the reconstruction of Lewis et al. (2014a). Briefly, the cropping land use area and changes to the grazing area (estimated using changing livestock numbers and assuming relatively consistent stocking rates) were compiled from the annual statistical registers. The total basin area was subtracted from these changing annual cropping and grazing area calculations to produce a time series of annual 'natural/conservation' land area. Annual Burdekin River discharge was compiled from DNRM (2019) and an earlier coral luminescent line reconstruction from Lough (2007). The annual discharge was used in association with suspended sediment event mean concentrations (EMC) for each land use to produce an annual sediment load calculation (Lewis et al., 2014a). This method does not take into account the mining and other land uses in the catchment at the time and hence only provides an estimation of the agricultural contribution to the sediment load.

The second method is termed 'Reconstruction 2 (coral Ba/Ca ratios)' which was taken from Chaiechi et al. (2016). Briefly, a relationship between the annual measured Burdekin River sediment loads presented in Kuhnert et al. (2012) and the 'accumulated Ba/Ca in the flood event' was established (method provided in Lewis et al., 2018) using the Ba/Ca ratios measured by McCulloch et al. (2003) in a coral core from Havannah Island. This relationship was then extended to the Ba/Ca dataset of McCulloch et al. (2003) to reconstruct annual sediment loads back to 1922 and the largest annual accumulated Ba/Ca in the flood

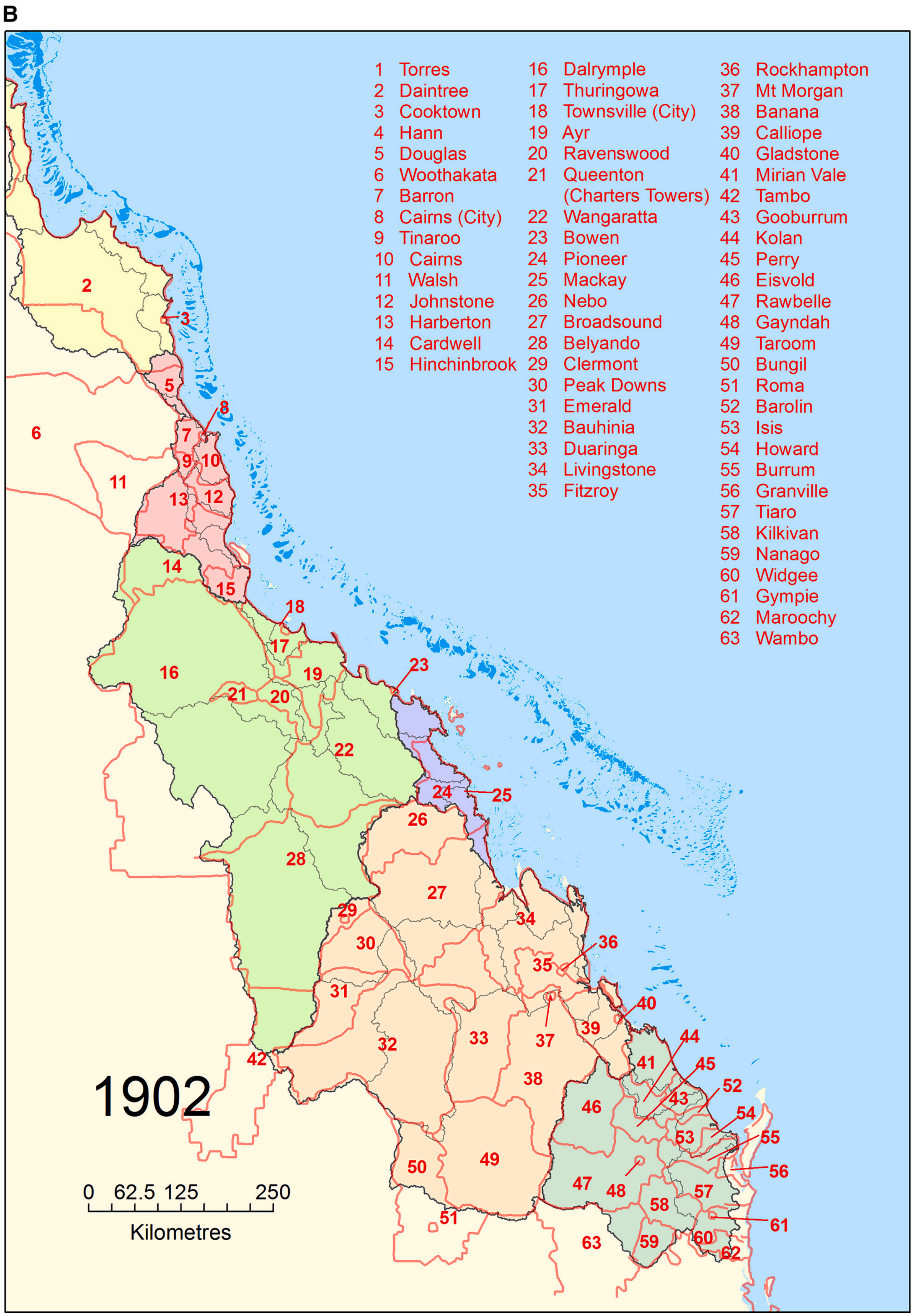


Fig. 2. (continued).

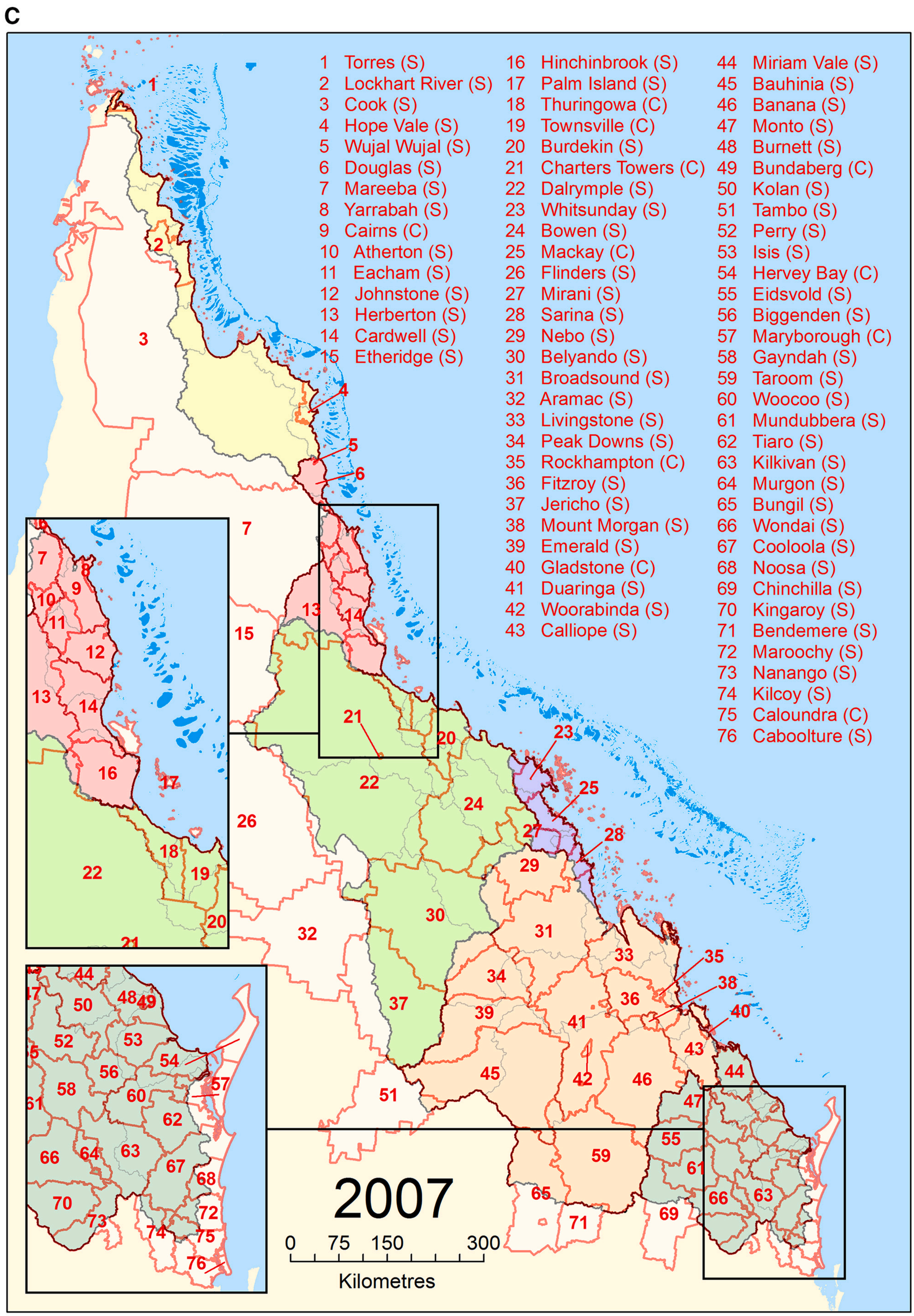


Fig. 2. (continued).

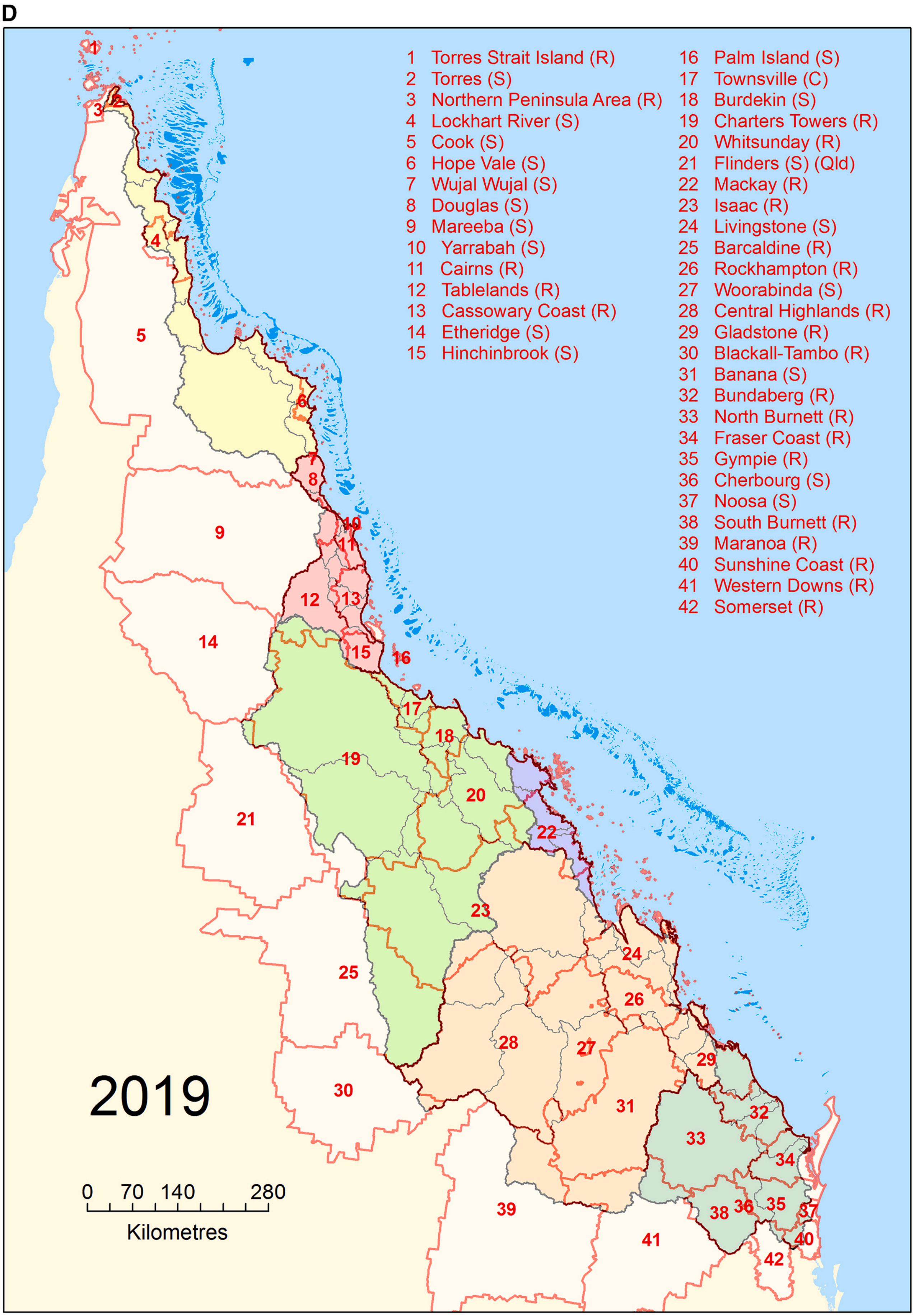


Fig. 2. (*continued*).

event per decade was used to report the highest annual load in each decade for the period 1850 to 1920.

We note that both these attempts to reconstruct annual Burdekin sediment loads have high uncertainty. Specifically the 'Reconstruction 1 (agriculture)' sediment load (Lewis et al., 2014a) does not capture all key industries such as mining which may have contributed elevated sediment loads particularly up until the early 1900s when sluicing and alluvial mining were utilised as a method to extract gold (e.g. Bartley et al., 2018). In addition, the changing spatial distribution of animal numbers across a climatically and geologically diverse basin, and changes in management practices in the grazing industry (e.g. additional fencing and watering points) would have likely resulted in a variable impact of grazing over time. While the coral core 'reconstructed sediment load' (Chaiechi et al., 2016) would not be influenced by these limitations, Lewis et al. (2018) has subsequently shown that the correlation between the annual measured Burdekin sediment load and the corresponding 'accumulated Ba/Ca in the flood event' was poor ($r^2 = 0.24$) and that in fact the annual peak Ba/Ca ratios provided a better correlation with sediment load ($r = 0.83$) (hence why we have also provided the annual peak Ba/Ca data).

4. Results

4.1. Population

The estimated resident human population (ERP) data for the GBRCA display three broad trends over the past 160 years (Fig. 4A). The first trend from 1860 to 1880 show a slowly increasing and relatively small ERP reaching 36,000 people by 1880; this period likely represents an underestimation in reporting given the rapid increase in numbers of European and Chinese across the GBRCA over this time due to the gold rush (and associated difficulties to keep track of people across a large and, at that time, remote area). It is noted that the ERP excludes the large numbers of people travelling through the GBRCA to gold diggings nearby including those at the Palmer River field (Kirkman, 1984). The second trend period reveals a steady increase from 87,000 in 1881 (note large jump from 1880) to 590,000 in 1975, including a decline of 7% during World War II. The third trend period 1976 to 2019 displays a more rapid increase in ERP from 640,000 to 1,200,000, respectively (Fig. 4A).

These three broad trend patterns were also apparent in the data from the NRM regions with the exception of the Cape York and Fitzroy NRM regions (and possibly Mackay Whitsunday) (Fig. 4B). The Cape York NRM region has had a fairly low and stable ERP over the entire 1860–2019 period with a slow and steady rise from the late 1960s reaching 26,000 in 2019 (Table 3). The Fitzroy NRM region ERP stabilised in the late 1980s at ~140,000 and has since displayed little growth (2019 ERP = 160,000) while the Mackay Whitsunday NRM region has possibly stabilised within the last decade (Fig. 4B).

More dynamic trends in the ERP data for the GBRCA were, however, revealed within the basin-scale data (Table 3; Supplementary material). These data show strong growth in the basins containing the larger cities (i.e. Barron and Russell Mulgrave Basins: Cairns; Ross Basin: Townsville; Pioneer and O'Connell Basins: Mackay; Fitzroy Basin: Rockhampton; Burnett and Burrum Basins: Bundaberg; Burrum and Mary Basins: Hervey Bay and Maryborough) while the remaining basins display relatively less growth over much of their time series (Supplementary material).

4.2. Livestock

The cattle and sheep industries have seen contrasting trajectories in the GBRCA over the study period, although both have been affected by

Table 2
Summary of the agricultural statistical reporting data compiled in this study.

Statistical reporting	Police/Petty Sessions districts	Local Authority Areas/Statistical Local Areas	Statistical Level Areas (SA2)
Reporting period	1860–1939	1941–2006	2011-present
Data sources	Statistics of the Colony/State of Queensland yearbooks	Statistics of the State of Queensland yearbooks (1941–1974), ABS Queensland Agricultural Industry yearbooks (1975–1982), Digitised data supplied by ABS (1983–2006)	ABS website (2008–2019)
Metrics compiled	Cattle (total; called 'horned cattle' 1869–1895); sheep (total); total extent of land under crop (also called 'total area under all crops'; sugar cane (including sum of areas 'cut for crushing' and 'stand-over plants'; also sum of 'for sugar' and 'green food for cattle'); bananas (including sum of areas 'bearing' and 'not yet bearing'); cotton (including sum of areas 'bearing' and 'not bearing')	All cattle (also 'total cattle', 'total cattle and calves' and 'cattle for all purposes excluding house cows'); total sheep (also sheep and lambs total number'); area/land under crop (also 'area of all crops (excluding pastures)'; 'total area used for crops'; 'Crops excluding pastures and grasses - total area'); sugar cane (total area; also sum of areas 'for crushing', 'plants' and 'stand-over and new cane'; also sum of areas of 'sugar cane cut for crushing' and 'sugar cane standover': 1995–1997); cotton (also 'cotton total area'); bananas (total area; also sum of areas "bearing' and 'not bearing')	Livestock – Cattle total; livestock – sheep total (also sheep and lambs total number); area of holding, land mainly used for agriculture –crops (also 'crops - total crops (including broadacre, hay, silage and horticulture)'); sugar cane (total area; also sum of 'broadacre crops - sugar cane cut for crushing' and sugar cane – standover from previous season'); bananas total area; cotton area planted (also irrigated and non-irrigated area)
Gaps in record	Continuous data but gaps between reporting periods (i.e. 1940)	For Livestock gaps include 1942, 1944, 1998–2000, 2002–2005, 2007–2010; For Cropping gaps include 1941–1944, 1946–1950, 1976–1977, 1990, 1998–2000, 2002–2005, 2007–2010 (although note NRM-scale data available in 2008–2010); the latter gaps represent changing protocols in data collection (i.e. census completed every 5 years)	2012–2015, 2017–2019 (although note NRM-scale data available for these periods); the gaps represent changing protocols in data collection (i.e. census completed every 5 years)
Notes	Changes to districts well documented in year-books which include: establishment of new districts (i.e. a new district split from one or more existing districts); the lumping of districts (a district was decommissioned and lumped into a surrounding district) or the renaming of a district area (see Supp. material)	District areas highly stable between 1941 and 1982; changes from 1983 reflect some 'blending' with the SA methods (i.e. while most districts had the same name and area the term used was 'SLA levels'). Changes in 1983–2006 period reflect renaming of district or splitting district into 'Part A' and 'Part B' sections (or inclusion of suburbs within major cities) (see Supp. material)	In most cases, the SA2 districts are at a finer resolution than the previous local authority areas with some exceptions of the more sparsely populated inland sections of the GBRCA (see Fig. 3D and Supp. material)

droughts and in particular the Federation Drought from 1895 to 1902 (Fig. 5A). Cattle numbers in the GBRCA grew steadily from 160,000 in 1860 to 3,300,000 head in 1894 before declining to a low of 950,000 in 1903 due to the arrival of the cattle tick from the Northern Territory and the drought (i.e. a reduction of >70%). The industry recovered to pre-1895 levels by 1921 (3,300,000) and numbers in the GBRCA were relatively steady with some ebbs and subsequent recoveries coinciding with drought periods until the early-mid 1970s (Fig. 5A). Cattle numbers then increased rapidly from 3,900,000 head in 1970 to 5,800,000 head in 1978 (Fig. 5A). The subsequent period has seen an initial decreasing trend to a low of 4,700,000 in 1988 followed by a gradual overall increasing trend peaking in 2014 at 6,300,000 head but punctuated by some declines coinciding with drought periods.

At the NRM regional scale, the cattle time series show the dominance of the Fitzroy, Burdekin and Burnett-Mary NRM regions which reflect the large areas available for grazing (Fig. 5B). In comparison, the Cape York, Wet Tropics and Mackay Whitsunday NRM regions have had relatively small total cattle numbers over the period. However, when stocking rates (cattle per km^2 of grazing land) are considered the data show that the wetter coastal basins within the Wet Tropics (note some of the cattle in this region are dairy cows on improved pastures) and Mackay Whitsunday region support larger stocking densities ($>$ 25 cattle per km^2) compared to the larger regions which are comparatively drier and further inland ($\sim$ 6 to 22 cattle per km^2) (Table 3; Fig. 5D). Whilst the lowest cattle numbers in the GBRCA associated with the Federation Drought occurred in 1903, the NRM time series data show that the Wet Tropics region recorded the lowest numbers in 1897 with the largest single year decline between 1895 (110,000 head) and 1896 (59,000) (Supplementary data). Other NRM regions recorded lower cattle numbers just after 1903 including Mackay Whitsunday (1904) and Cape York (1905). Interestingly, cattle numbers in the Fitzroy, Burdekin and Burnett-Mary NRM regions over the 1860 to ~1930s period were similar and followed similar trends before the Fitzroy NRM region displayed a sustained rise in the subsequent period due to extensive tree/shrub clearing and the establishment of buffel grass (*Cenchrus ciliaris*) pastures (i.e. from 880,000 in 1927 to a peak of 3,600,000 head in 2014 with a particularly steep rise in the 1970s). In contrast, the Burdekin NRM region has displayed an overall slower rising trend (630,000 in 1931 to peak of 1,700,000 head in 2009 and down to 1,300,000 head in 2019) and the Burnett-Mary NRM region displaying an overall steady trend (810,000 in 1926 to 930,000 head in 2019) (Fig. 5B). The Fitzroy NRM region today supports over 55% of the total cattle numbers in the GBRCA (Table 3).

Sheep numbers in the GBRCA displayed an initial steep increase from 1,500,000 in 1860 to a peak of 4,600,000 head in 1867 before collapsing to 650,000 in 1886 (i.e. a reduction of >85%; Fig. 5A). The industry never fully recovered and experienced further large losses during the Federation Drought (from 1,500,000 in 1899 to 410,000 in 1902; i.e. a reduction of >70%). The sheep numbers then increased to a peak of 2,200,000 head in 1914 before another sharp decline to 890,000 in 1916 and a steady recovery to 2,100,000 head by 1938. The industry declined during and shortly after World War II (650,000 head in 1952) but slightly recovered again to a peak of 1,300,000 in 1960 before declining and collapsing to <200,000 head by 1979 and has never recovered since (Fig. 5A). The ABS (2020a) report 47,000 sheep in the GBRCA in 2019, which is the highest since 2010 (51,000) and represents an order of magnitude increase since the previous year (i.e. 4900 sheep in 2018). On an NRM scale the relatively large increases between 2018 and 2019 were reported for the Fitzroy, Mackay Whitsunday and Burnett Mary NRM regions, although at this stage it may be that this represents an 'anomalous year' rather than a sustained shift towards increased sheep production in the GBRCA.

The sheep time series at the NRM region scale show the dominance of the Fitzroy, Burnett-Mary and Burdekin NRM regions when peak sheep numbers were recorded in the GBRCA in 1867 (2,600,000, 1100,000 and 800,000 head, respectively) (Fig. 5C). Following this period, the Burnett-Mary NRM region sharply declined and never recovered while both the Fitzroy and Burdekin NRM regions displayed similar trends outlined for the GBRCA data (Fig. 5C). Indeed, while the Fitzroy NRM region had much higher sheep numbers in the 1860 to ~1880 period, the Burdekin NRM region had similar numbers to the Fitzroy NRM region from the 1880s to the ~1920s before the Fitzroy again become the dominant producer (Fig. 5C). Interestingly, individual district level data appear to show the movement of sheep to coastal areas during the Federation Drought; for example, sheep numbers in the Bowen district increased from 223 in 1896 to 33,730 head in 1902 (Supplementary data). The finer scale data also reveal that sheep numbers were particularly concentrated in the southern parts of the GBRCA and were concentrated in the larger basins including the Fitzroy and Burnett Basins and Belyando-Suttor sub-basin of the Burdekin (Supplementary material).

4.3. *Total area under crops*

The total area under cropping in the GBRCA follow three major trend periods over the study period (Fig. 6A). The first trend period displays the gradual steady growth of the cropping industry from 101 ha in 1860 to 380,000 ha by 1958. The second period saw a steep rise in the area under cropping in the GBRCA from 380,000 ha in 1958 to 1,400,000 ha in 1986 while the most recent third period has been characterised by sharp fluctuations in area ranging from the current 830,000 ha (2019) to a peak of 1,500,000 ha in 2009 with at least some of the declines explained by drought periods (Fig. 6A).

The Fitzroy NRM region has had the largest area under cropping in the GBRCA since the mid-1960s and as a result has driven the overall GBRCA trends (Fig. 6B). Indeed the area under crops in the Fitzroy NRM region has increased greatly from 55,000 ha in 1957 to 360,000 ha in 1969 and to 750,000 ha in 1986 (Fig. 6B). Prior to the early 1960s, the Burnett-Mary NRM region had the highest total area under cropping followed by the Wet Tropics and Mackay Whitsunday NRM regions. The Wet Tropics, Burdekin and Mackay Whitsunday NRM regions have seen modest growth (2 to 6-fold increases) in area under cropping since the 1960s while the area under cropping in the Burnett-Mary NRM region has remained steady or slightly declined. There has been little cropping ($<$ 10,000 ha) in the Cape York NRM region relative to the other five regions (Fig. 6B).

The 'other crops' metric for each NRM region (Fig. 6C) was calculated by the difference between the annual total area under cropping and the corresponding summed area of sugar cane, bananas and cotton. This metric predominately captures the broad acre grain crops such as sorghum, maize, wheat, barley, oats, millet and pasture seed production. In that regard, the numbers and trends of these data for the Fitzroy and Burnett Mary NRM regions were identical to the total area under crops which highlight the dominance of grain crops particularly within their larger basins. Conversely, the cropping area in the Wet Tropics and Mackay Whitsunday NRM regions is dominated by sugar cane (Fig. 6C). The Burdekin NRM region hosts both broad acre grain crops on basalt soils in the southern part of the Burdekin Basin, and sugar cane crops on the coastal plain (in particular lower Haughton and Burdekin Basins) and hence while 'other crops' comprise a smaller proportion of total crops, a similar trend in the data to the total crops was evident from ~1980 (Fig. 6C). We note that the other crops metric also captures horticulture, although this land use is only noteworthy in the Barron, Black, Haughton, Don, Proserpine, Kolan, Burrum and Mary Basins (see Table 1; Supplementary material).

4.4. *Sugar cane*

Sugar cane was first recorded in the GBRCA in 1864 and the industry proceeded to grow slowly until the early 1880s when the area in the GBRCA tripled within a few years (Fig. 7). During the 1880s to 1890s the sugar cane area in the GBRCA remained fairly consistent before

A

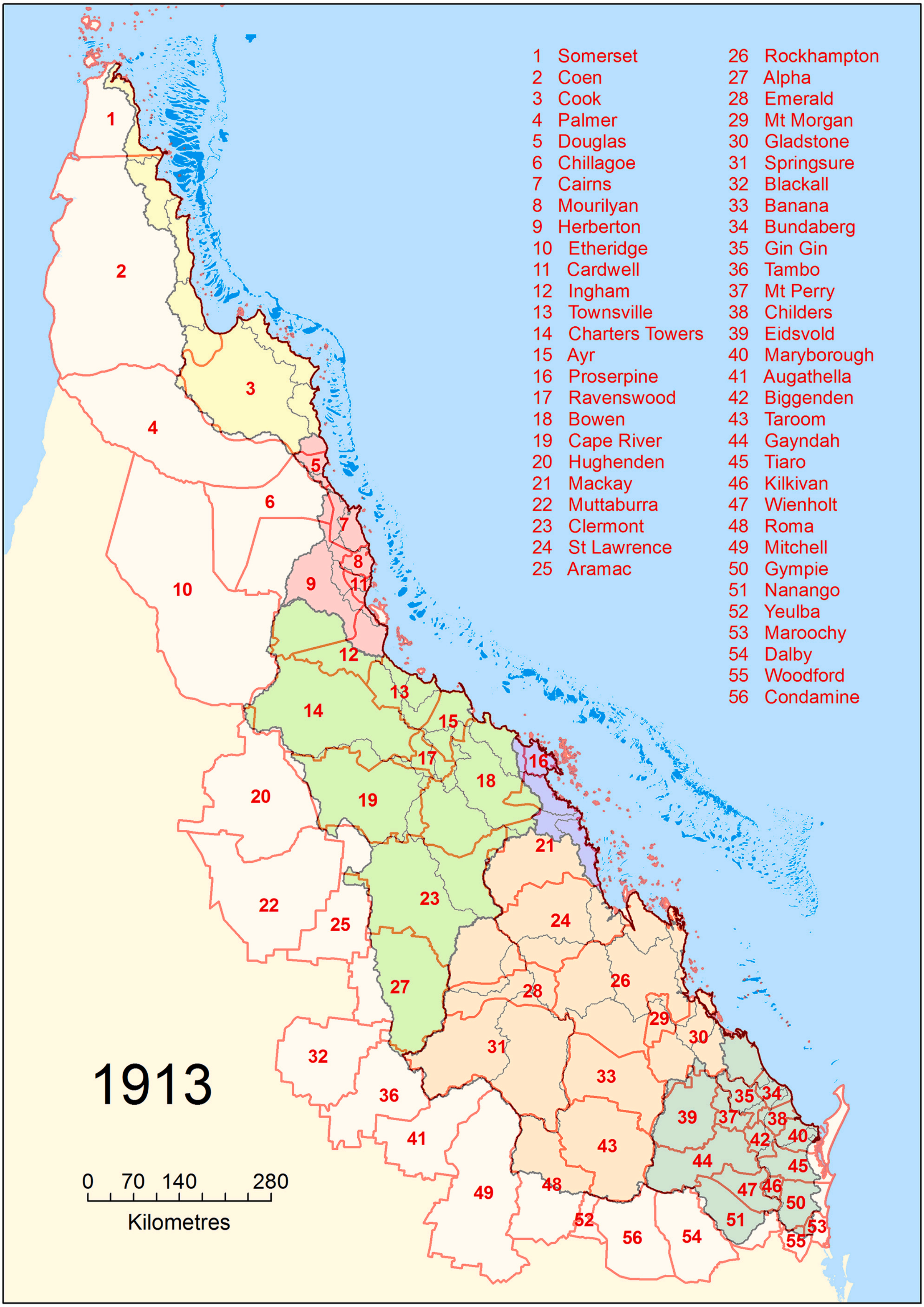

1 Somerset
2 Coen
3 Cook
4 Palmer
5 Douglas
6 Chillagoe
7 Cairns
8 Mourilyan
9 Herberton
10 Etheridge
11 Cardwell
12 Ingham
13 Townsville
14 Charters Towers
15 Ayr
16 Proserpine
17 Ravenswood
18 Bowen
19 Cape River
20 Hughenden
21 Mackay
22 Muttaburra
23 Clermont
24 St Lawrence
25 Aramac
26 Rockhampton
27 Alpha
28 Emerald
29 Mt Morgan
30 Gladstone
31 Springsure
32 Blackall
33 Banana
34 Bundaberg
35 Gin Gin
36 Tambo
37 Mt Perry
38 Childers
39 Eidsvold
40 Maryborough
41 Augathella
42 Biggenden
43 Taroom
44 Gayndah
45 Tiaro
46 Kilkivan
47 Wienholt
48 Roma
49 Mitchell
50 Gympie
51 Nanango
52 Yeulba
53 Maroochy
54 Dalby
55 Woodford
56 Condamine
1913
0 70 140 280
Kilometres

Fig. 3. An overview of the changes in spatial units which have been used for reporting agricultural data from 1860 to 2016 (note outlines of the basin and shadings for NRM regions; see Fig. 1 for more details). More details on how these districts changed over time (including full page versions of these figures) are provided in the Supplementary materials.

displaying strong growth in area from 1902 (34,000 ha) to 1974 (260,000 ha). Over that time, there were some periods with limited to no growth (or even some declines in area) such as during and shortly after World War II and during the early 1960s (Fig. 7). Rapid growth of the sugar industry occurred between 1974 (260,000 ha) and 1983 (360,000 ha). The area of sugar cane in the GBRCA peaked in 2001 at 480,000 ha, and has been relatively consistent over the past decade (400,000 ha in 2019) (Fig. 7).

The trends in sugar cane area described for the GBRCA from 1860 to 1980 are generally mirrored in each NRM region (Fig. 8A). However, since 1980 more pronounced differences have emerged between the NRM regions, with an overall decline in the sugar cane area in the Burnett-Mary NRM region between 1982 (75,000 ha) and 2019 (47,000 ha) and an increase in area in the Burdekin NRM region over the same period due to the greater availability of irrigation water following the completion of the Burdekin Falls Dam in 1987 (39,000 ha in 1980 to 76,000 ha in 2019) (Fig. 8A). In particular, a strong period of growth in sugar cane area in the Burdekin NRM region occurred between 1990 (46,000 ha) and 1994 (64,000 ha). The peak in the Burdekin NRM region sugar cane area in 2016 (140,000 ha) appears anomalous as the years on either side reveal much lower numbers (i.e. 98,000 ha in 2015 and 85,000 ha in 2017; for further discussion see ‘dataset accuracy and interpretation’ section in the Supplementary material). The sugar cane area in the Wet Tropics and Mackay Whitsunday NRM regions have been relatively consistent since 1982 with some exceptions of annual fluctuations (Fig. 8A). A small area (520 ha in 2019) of sugar cane persists in the Isaac-Connors sub-basin of the Fitzroy NRM region and no sugar cane has been recorded in the Cape York NRM region since 2001 (Supplementary data). The sugar cane areas within the NRM regions are generally indicative of but do not accurately predict the regional tonnages of sugar cane crushed at sugar mills. In 2019 the NRM regions in descending order of sugar cane areas are the Mackay Whitsunday (138,000 ha), Wet Tropics (136,000 ha), Burdekin (76,000 ha) and Burnett-Mary (47,000 ha) NRM regions. In comparison, using the corresponding SA2 data, the ABS (2020c) report for 2019–20 that the Burdekin NRM region, where the whole sugar cane crop is irrigated rather than rainfed, produces by far the highest tonnes of sugar cane harvested (11,964,800 t) followed by the Mackay Whitsunday (7,373,300 t), Wet Tropics (5,626,000 t) and Burnett-Mary (2,614,400 t) NRM regions.

4.5. *Bananas*

The banana industry in the GBRCA has experienced two phases of growth over the past 160 years (Fig. 7). The first phase occurred from the 1880s where the industry grew from 74 ha in 1881 peaking at 5100 ha in 1928 with a period of particularly strong growth between 1919 (1300 ha) and 1928 (5100 ha). The industry declined considerably thereafter falling to only 825 ha in the GBRCA by 1935 and remaining below 1100 ha until 1975. The second phase of growth occurred from 1978 (1300 ha) and was characterised by steep growth to a peak of 16,000 ha in 2016, although there have been some large annual fluctuations in the total area since 2006 (Fig. 7).

The NRM region time series show that the Wet Tropics NRM region (10,000 ha) dominates the banana area in the GBRCA with <40 ha in the other five NRM regions (Fig. 8B; Table 3). Interestingly, the NRM region time series show that it was initially the Wet Tropics NRM region that drove the first phase of growth in the banana industry from the 1880s to ~1917 (peaked at 2000 ha in 1904) before a collapse in this area (i.e. < 500 ha by 1917) coincided with a rise in the Burnett-Mary NRM region from 1915, which peaked in 1928 (4600 ha) and then collapsed by 1936 (i.e. < 500 ha) (Fig. 8B).

4.6. *Cotton*

While cotton has been grown in the GBRCA from the first record in 1860 (5 ha), it wasn’t until the early 1920s that it emerged as a widely grown crop (Fig. 7). Indeed, before 1921 the maximum cotton area in the GBRCA was 344 ha recorded in 1863 and for most years between 1860 and 1920 the total cotton area in the GBRCA was <100 ha. The cotton area then increased considerably from 32 ha in 1920 to 790 ha in 1921 to 10,000 ha in 1922 to 21,000 ha in 1923 (Fig. 7). The annual total area fluctuated between 10,000 and 34,000 ha between 1922 and 1944, peaking at 34,000 ha in 1933 before generally declining after 1945. The cotton industry saw renewed growth in area during the 1980s (~20,000 ha with a peak area of 48,000 ha in 1988). Over the past two decades the annual cotton area in the GBRCA has fluctuated considerably ranging from a low of 5100 ha in 2008 to a high of 55,000 ha in 2018 (Fig. 7). As of 2019, the cotton area in the GBRCA was 18,000 ha (Table 3).

The NRM region time series for cotton shows that it was the Fitzroy and Burnett-Mary NRM regions that were the dominant cotton producers from the 1920s to early 1940s before the Fitzroy NRM region became the sole key cotton producer (Fig. 8C). In 2019, the Fitzroy NRM region had the highest total cotton area of 17,000 ha followed by 600 ha in the Burnett-Mary NRM region and 420 ha in the Burdekin NRM region (Table 3). The other three NRM regions recorded no cotton in 2019.

5. Discussion

5.1. *Population changes*

Our data show that the human population in the GBRCA and most NRM regions continue to grow over the data time series (Fig. 4). However, the ERP data compilation at the finer basin scale clearly document two key population trends in the GBRCA, that of consistent and strong growth in the basins that host large cities and the fairly slow to little/no growth in the basins that host the small townships (Supplementary material). Indeed, some of the early gold rush towns such as Charters Towers and Ravenswood have even seen considerable declines in the population since the late 1800s to early 1900s (peaked at ~25,000 and ~ 5000, respectively compared to 8100 and 260 in the 2016 census; ABS, 2020b). In that regard, these trends are largely driven by infrastructure and economies (jobs: major cities) and mining and agriculture (smaller towns). Specifically, the decline in population is known as rural decline where the agriculture and mining industries have become more efficient with less labour requirements resulting in the rural youth moving to the larger urban centres (Measham and Fleming, 2014). The rapid growth in the larger cities also highlight the challenges for town planners including the selection of suitable land to open up for new urban developments (i.e. avoid flood prone areas) as well as general planning of relevant design and infrastructure needs to support these growing communities.

5.2. *Livestock changes*

At separation, the Colony of Queensland passed the Unoccupied Crown Lands Occupation Act (1860) which granted all new lands claimed by squatters to be stocked at 25 head of sheep or 5 head of cattle per square mile (Kingston, 1965). This legislation generated a land rush

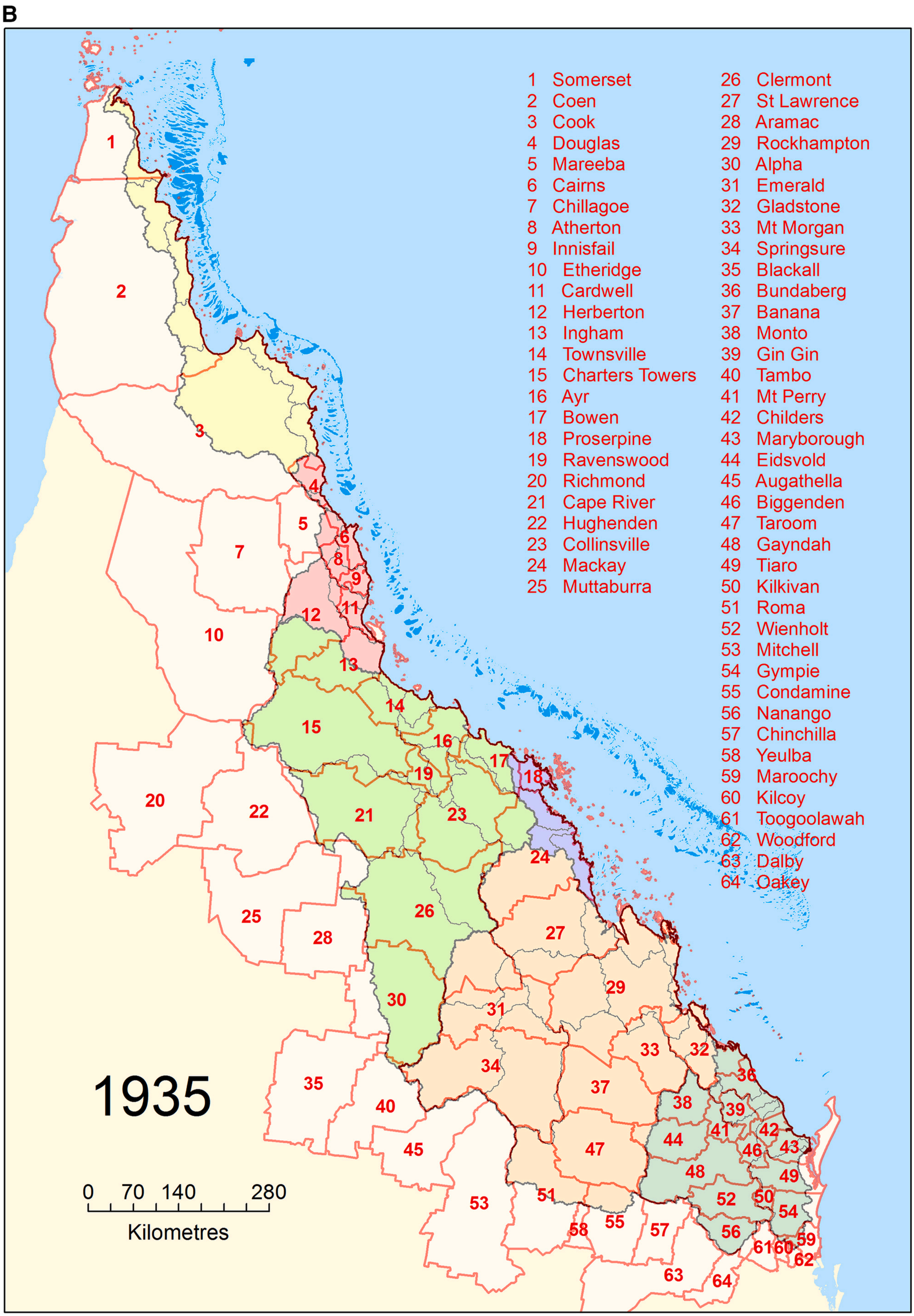
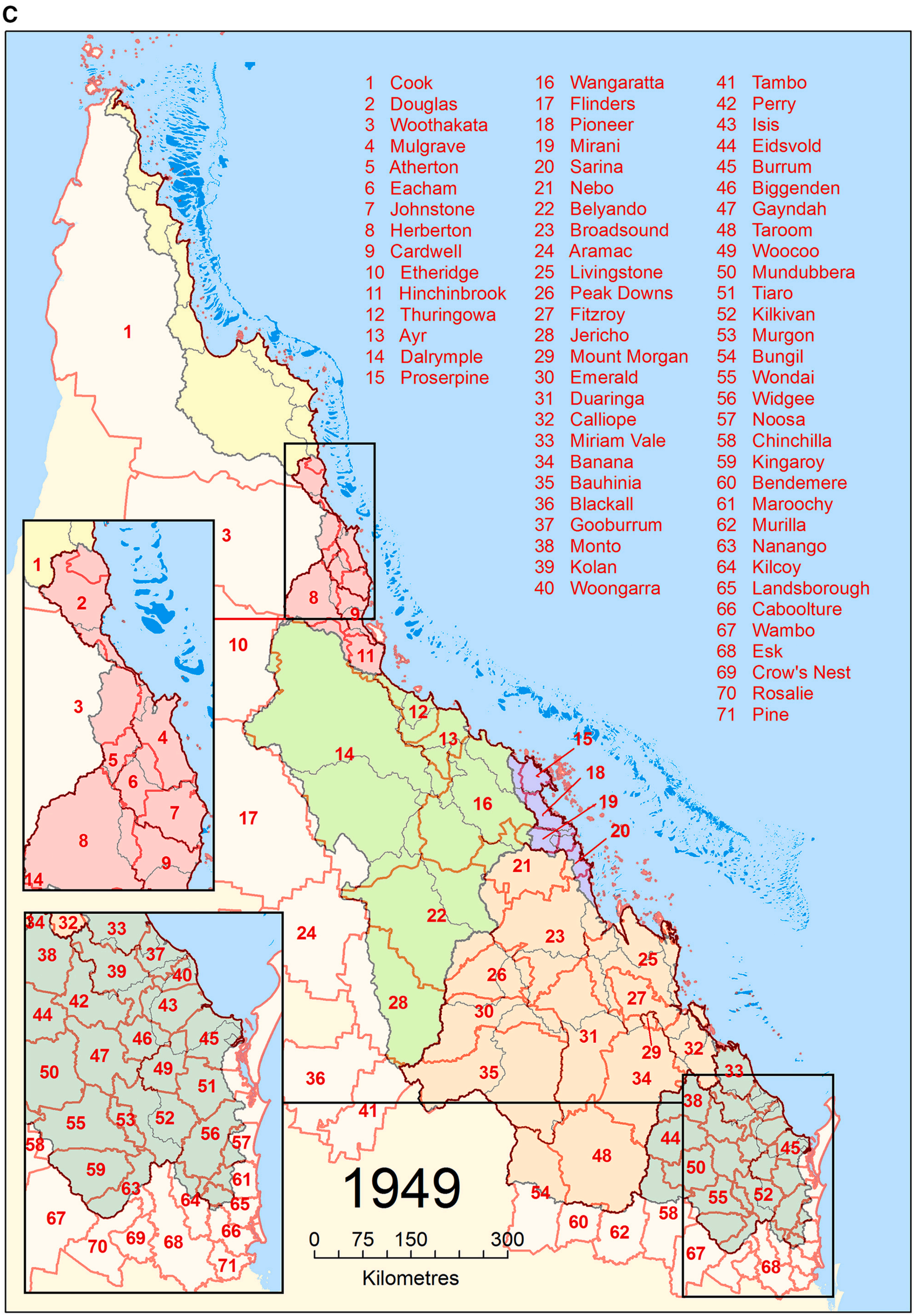


Fig. 3. (*continued*).



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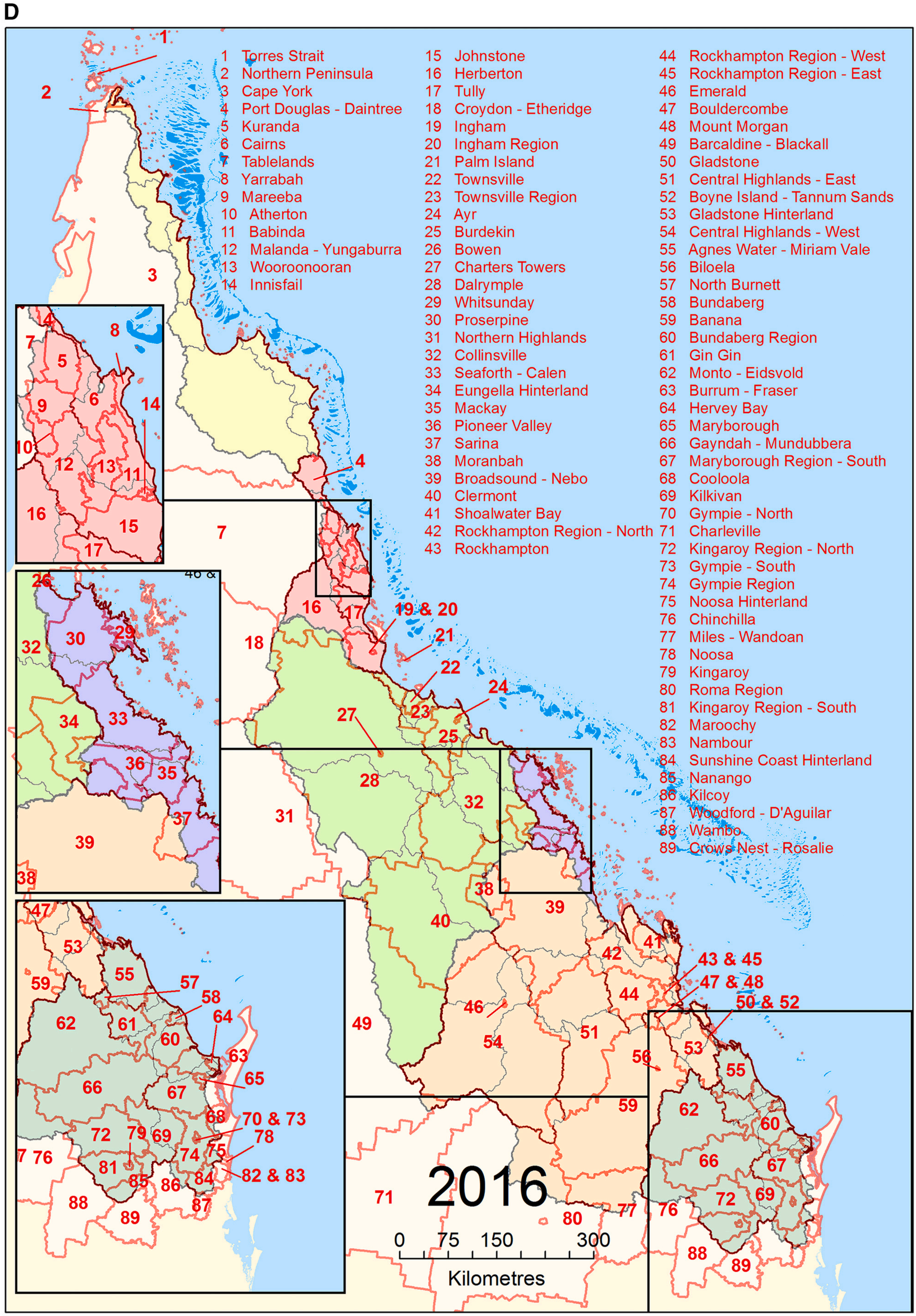

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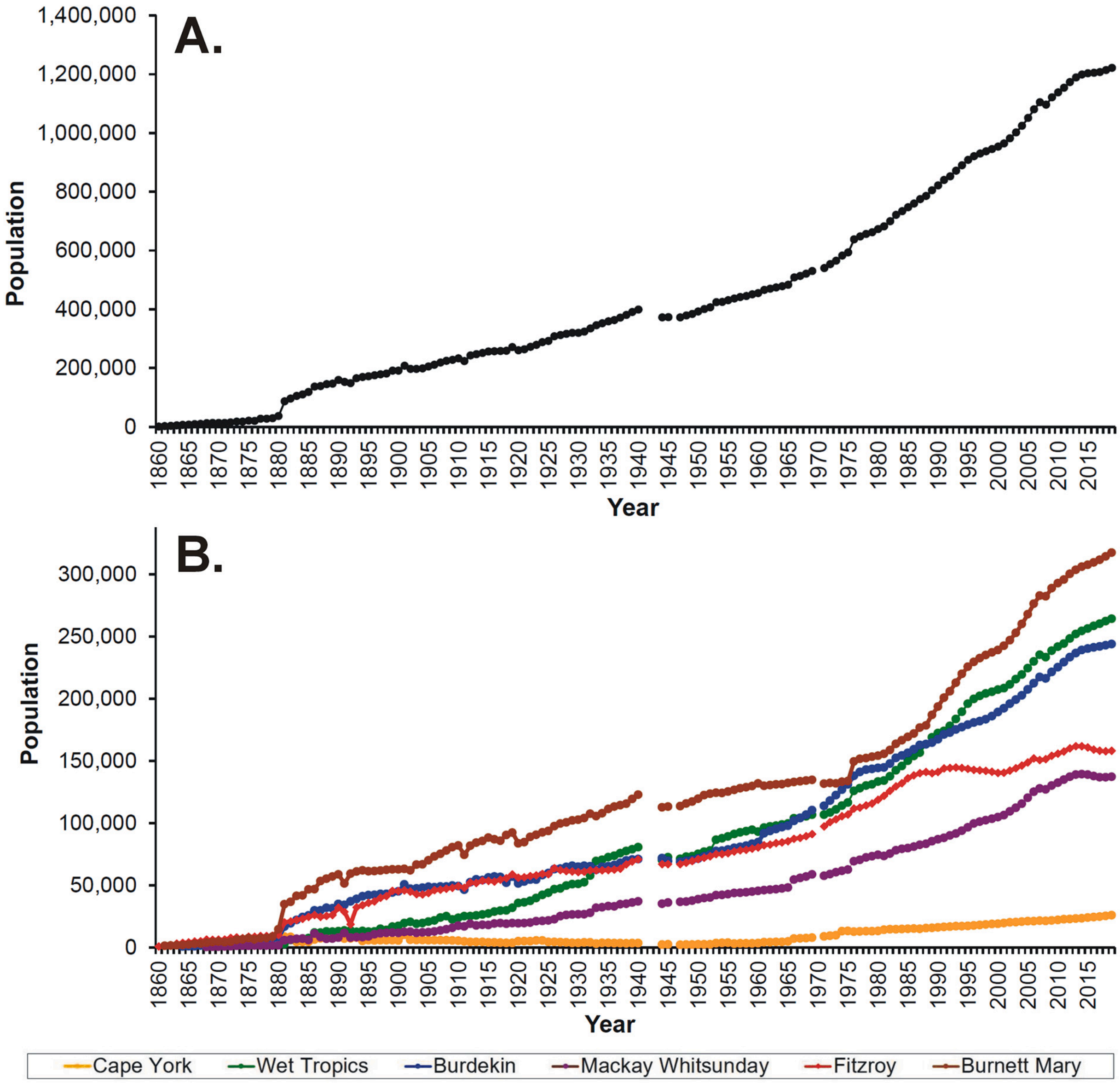

Fig. 4. Human population time series data for the Great Barrier Reef catchment area (A) and the six Natural Resource Management Regions (B) from 1860 to 2019.

throughout the Leichhardt and Kennedy Pastoral Districts with squatters and their associates driving herds in order to claim title. Our livestock compilation documents both the rise of the cattle industry and the rise and fall of the sheep industry in the GBRCA over the 1860 to 2019 period (Fig. 5). The time series also reveal finer temporal scale periods of marked increases as new land was opened up for production through infrastructure such the installation of new watering points and the dramatic falls due to influence of ticks, droughts, floods, diseases and pests (Fig. 5). In general, the expansion of the cattle industry from the 1860s to mid-1890s was largely facilitated by the demand from the miners at the various gold fields (Gilbert and Brodie, 2001). At the NRM region scale, the finer spatial data reveal the effects of the tick epidemic particularly in the Wet Tropics, Burdekin and Fitzroy NRM regions in the mid-1890s (Bolton, 1963) as well as the widespread devastation associated with the following Federation Drought (May, 1984; Daly, 1994). In a landmark study, Dan Daly (1994) questions the definition and influence of drought on Queensland's livestock numbers. In that regard, Daly (1994) argues that drought declarations have historically been overused and suggests that the 'Gibbs' disaster drought' definition is a better reflection of drought as these are more statistically valid representations and have an ~18 year recurrence interval (marked as 'S' in Fig. 5A). Daly (1994) also recognises that other factors may have caused livestock numbers to decline during designated drought periods including the possible misreporting of statistical numbers (see dataset accuracy and interpretation section in the Supplementary material), ticks (particularly in the 1890s), pasture degradation from plagues of rabbits (southern Queensland only) and kangaroos (facilitated by improved water availability), sheep predation by dingoes, and weed infestations (e.g. prickly pear) (Australian Prickly Pear Board, 1925; Daly, 1994). In fact, Daly (1983, 1994) argues that the largest influence on livestock numbers in Queensland is related to economics.

Except for the Fitzroy NRM region which has continued to record growing cattle numbers over the last decade (current peak in 2014), the other regions have experienced either slower growth or a relative stabilisation over the past 20 to 30 years. The rapid growth in the Fitzroy NRM region facilitated by the clearing of the Brigalow vegetation since the 1960–70s has seen this region support over 55% of the cattle numbers in the GBRCA. The large fluctuations in cattle numbers in the Fitzroy NRM region over the last ~15 years suggest that numbers have perhaps begun to stabilise as carrying capacity in the region is reached,

Table 3
Summary of the latest available population and land use data from the ABS for each basin, NRM and the Great Barrier Reef catchment area. These data include population from 2019; basin-scale agricultural statistics from 2016 (Cape York basins and NRM are the exception with data from 2006) and; NRM region-scale agriculture statistics from 2019 (hence note the different years between basin and NRM-scale data which is why the basins do not add up to their respective NRM region). The bolded text represent the data at the NRM region and Great Barrier Reef catchment scales.

Basin/Region	Area km^2	Population	Cattle numbers	Cattle per km^2 of grazing land	Total Cropping Area km^2	Sugarcane km^2 (% of basin)	Bananas km^2	Cotton km^2
Jacky Jacky Creek	2963	1088						
Olive Pascoe River	4180	1						
Lockhart River	2883	753						
Stewart River	2743	59	620	9.1				
Normanby River	24,399	507	40,000	3.1	17			
Jeannie River	3638	85	59	0.2				
Endeavour River	2182	3762	5200	5.7	3.2			
Torres Strait		14,829						
Cape York NRM	**42,988**	**17,255**	**45,000**	**3.8**	**22**		**0.18**	
Daintree River	2107	3453	930	5.0	27	27 (1.3)		
Mossman River	473	24,978	17	0.9	28	28 (5.9)		
Barron River	2188	74,714	18,000	26	151	75 (3.4)	18	
Mulgrave-Russell River	1983	109,192	4300	51	213	200 (10)	14	
Johnstone River	2325	23,199	46,000	86	239	155 (6.7)	25	
Tully-Murray River	2790	10,815	14,000	75	409	300 (11)	96	
Herbert River	9844	17,899	74,000	14	511	492 (5.0)	1.3	
Wet Tropics NRM	**21,710**	**264,250**	**140,000**	**20**	**1572**	**1359 (6.3)**	**100**	
Black River	1057	14,763	3200	7.3	11	7.0 (0.7)	0.03	
Ross River	1707	182,940	9100	11	4.6	0.3 (0.02)		
Haughton River	4051	9334	35,000	13	935	865 (21)	0.02	
Upper Burdekin/Cape	60,668	11,739	430,000	8.1	10			
Belyando/Suttor	35,352	1819	520,000	11	618	0.85 (0.00)		
Bowen/Broken/Bogie/ East Burdekin	34,100	13,683	150,000	11	598	554 (1.6)	0.01	
Burdekin River	130,120	27,241	1,100,000	9.5	1227	554 (0.43)	0.01	
Don River	3736	9652	25,000	9.3	40	1.3 (0.03)		
Burdekin NRM	**140,671**	**243,930**	**1,300,000**	**11**	**1391**	**763 (0.54)**	**0.02**	**4.2**
Proserpine River	2494	19,658	28,000	25	162	153 (6.1)		
O’Connell River	2387	42,035	39,000	40	172	164 (6.9)	0.05	
Pioneer River	1572	49,975	18,000	48	209	205 (13)	0.01	
Plane Creek	2539	25,565	41,000	68	419	387 (15)	0.02	
Mackay Whitsunday NRM	**8992**	**137,233**	**130,000**	**41**	**1392**	**1377 (15)**	**0.09**	
Styx River	3013	447	47,000	20	0.8			
Shoalwater Creek	3601	190	34,000	20	0.9			
Water Park Creek	1836	25,703	5000	17	9.9			
Isaac/Connors/McKenzie	35,354	8501	550,000	19	345	10 (0.03)		1.8
Nogoa/Theresa/Comet	44,959	33,087	730,000	23	1649	0.29 (0.00)		155
Dawson	50,734	21,061	920,000	24	1306			59
Lower Fitzroy	11,505	95,561	170,000	19	42			
Fitzroy River	142,552	158,210	2,400,000	22	3342	11 (0.01)		215
Calliope River	2241	43,501	37,000	22	7.4			
Boyne River	2496	13,570	34,000	19	1.9			
Fitzroy NRM	**155,740**	**241,621**	**3,100,000**	**26**	**2579**	**5.2 (0.00)**		**170**
Baffle Creek	4085	8929	37,000	14	14	3.1 (0.08)		
Kolan River	2901	8627	43,000	21	111	70 (2.4)		
Burnett River	33,207	104,366	550,000	22	729	134 (0.4)	0.23	4.4
Burrum River	3362	81,263	18,000	13	246	169 (5.0)	0.01	
Mary River	9466	114,264	140,000	27	150	90 (1.0)	0.07	
Burnett Mary NRM	**53,021**	**317,449**	**930,000**	**25**	**1304**	**471 (0.89)**	**0.35**	**5.9**
GBR Total	**423,122**	**1,221,738**	**5,600,000**	**19**	**8260**	**3975 (0.94)**	**102**	**180**

although time will tell.

The cattle time series also reflects the ever improving capability of the industry to absorb the effects of less water and pasture during drought conditions (as well as better pest and disease control mechanisms and transport networks) whereby the catastrophic losses (> 70% of stock; but see critique by Daly (1994) discussed in the dataset accuracy and interpretation section in the Supplementary material) of the Federation Drought have not been repeated (Fig. 5). Indeed, the droughts that have occurred since have seen either relatively smaller stock declines (generally <20%) or a general stabilisation of stock numbers, presumably due to the availability of improved management options such as the ability to draw on groundwater resources, movement of stock to areas with better pastures, the selection of more drought-tolerant breeds and to import feed or use supplements (e.g. urea licks). In most cases, the increases in cattle numbers have been offset by the increased availability of grazing land area and as such cattle stocking rates have remained relatively stable in most regions (Abbott and McAllister, 2004). When the livestock data are converted to adult equivalent per grazing area within each NRM region, the wetter areas including the Mackay Whitsunday and Wet Tropics regions have the highest stocking rates (Fig. 5D). These higher rates are primarily the result of the relatively higher pasture yields that are sustained in these wetter areas.

In contrast to the cattle industry, the major challenges facing the sheep industry in the GBRCA such as lowered demand/prices (for wool or mutton), drought and availability of water, the influence of various spear grasses (mainly *Heteropogon spp.*) on fleece quality and animal health, the reduction in pasture and poor performance in the wetter coastal basins could not be resolved (Bolton, 1963; Menghetti, 1992; Daly, 1994). Indeed, within two-three decades after the introduction of

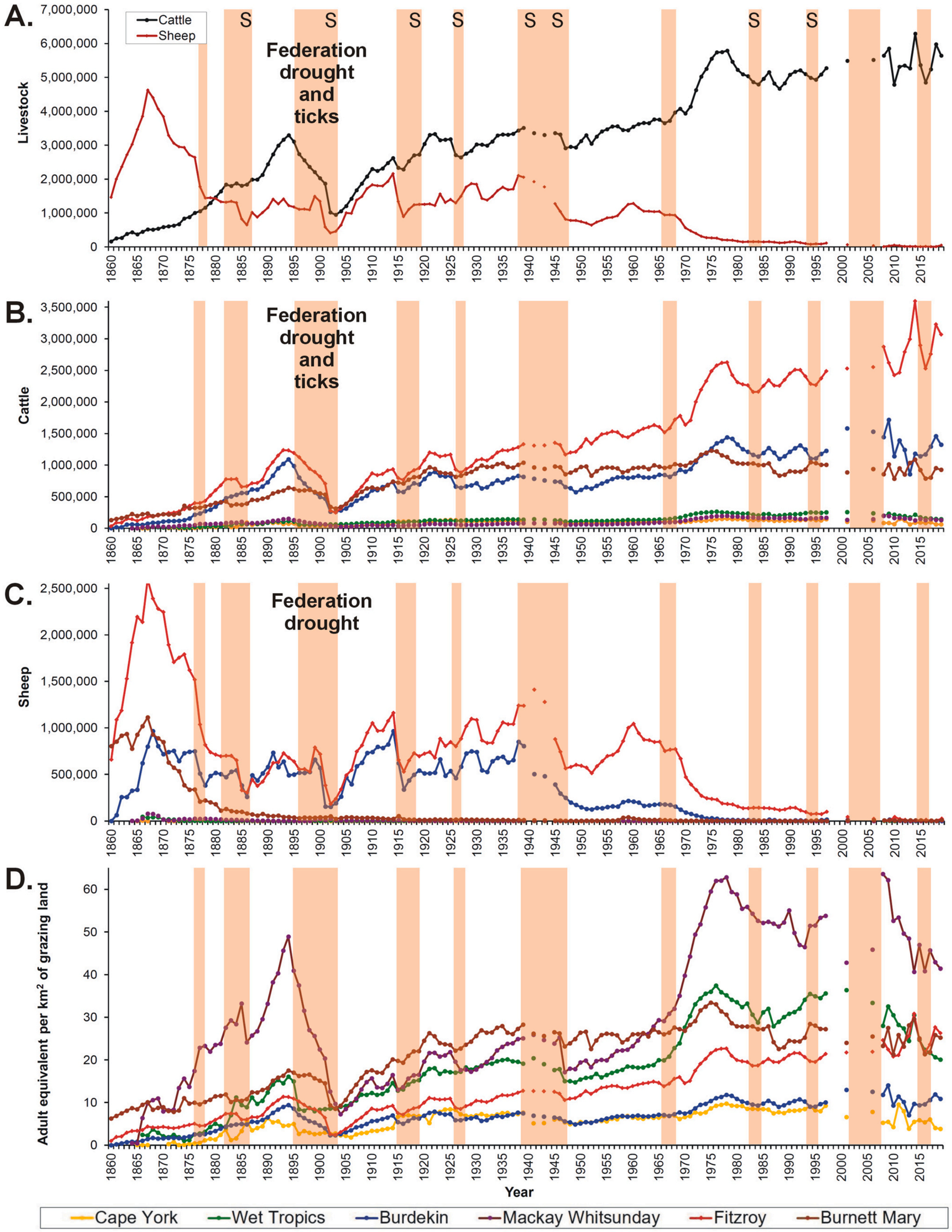

Fig. 5. Livestock data time series for the Great Barrier Reef catchment area (A) and cattle (B), sheep (C) and livestock per square kilometre (D) time series for the NRM regions from 1860 to 2019. Key drought periods are highlighted (orange vertical bars) including the severe droughts (listed as an 'S') defined as 'Gibbs' disaster droughts' by Daly (1994).

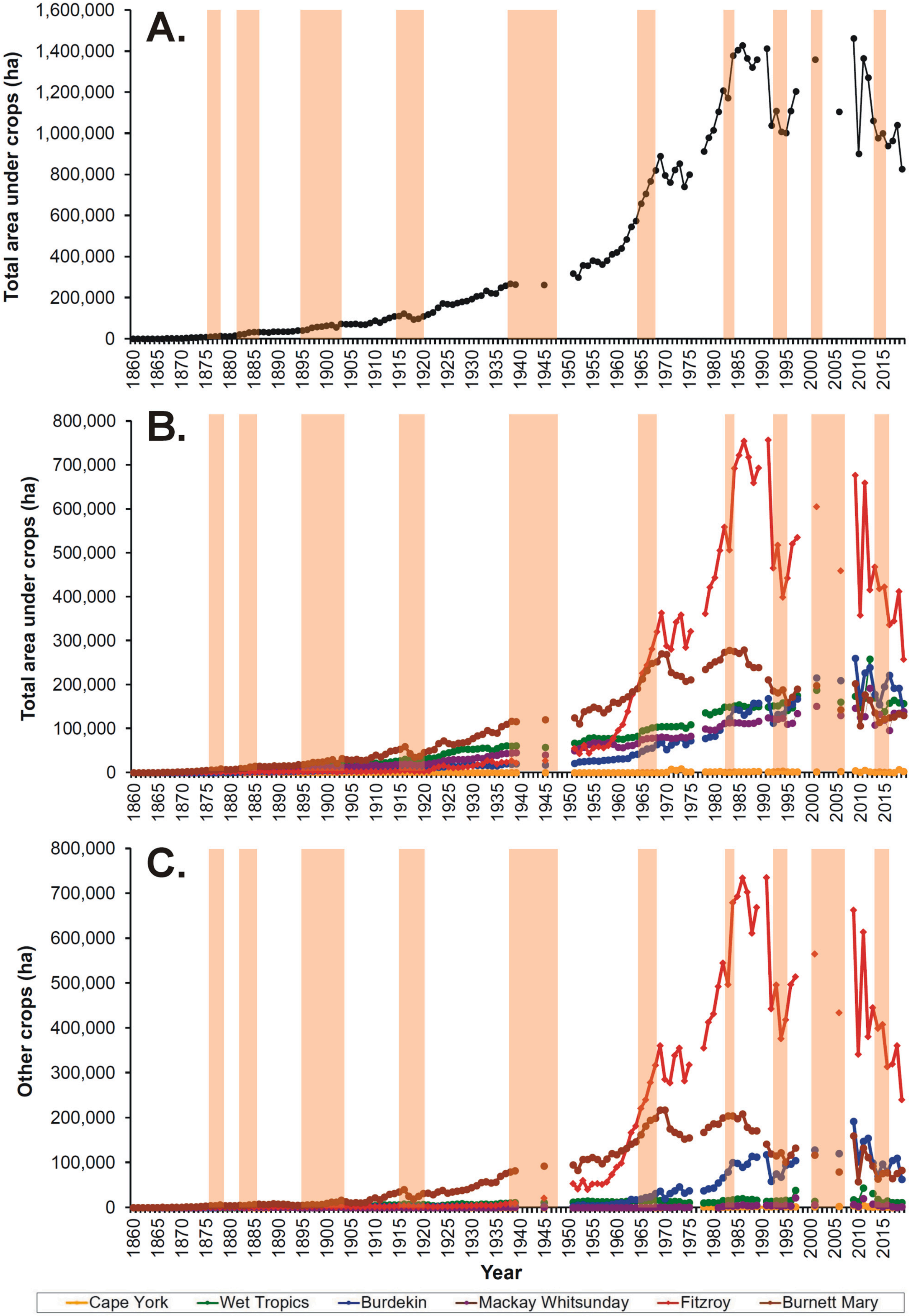

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Fig. 6. Total area under cropping time series (ha) for the Great Barrier Reef catchment area (A) and the NRM regions (B) and other crops in the NRM regions (C). The key drought periods are highlighted by the orange vertical bars. The key crops which dominate the total cropping series are grain crops and sugar cane. The other crops metric (C) is designed to capture the grain crops on their own.

sheep and cattle in the GBRCA, sheep went from the dominant commodity to of secondary importance relative to the cattle industry.

The first major decline in the sheep industry during the late 1860s to 1870s was triggered by reduced prices and demand as well as the unsuitable terrain (particularly coastal areas) where sheep suffered worms, footrot, fleece rot and disease as well as impediments from spear grass (Daly, 1994). The industry persisted and saw further declines in drought periods and subsequent recoveries but by the 1970s the sheep industry was negligible in the GBRCA (Fig. 5A). For a more comprehensive overview of the cattle and sheep industries including a more thorough interpretation of the statistics (i.e. the inclusion of slaughtering statistics and economics) the reader is referred to Daly (1983, 1994). Other valuable resources include Allingham (1976), May (1984), McDonald (1985) and references therein.

5.3. Cropping changes

The changes in the total area under cropping in the GBRCA are largely driven by the basins with large areas in particular, the Fitzroy followed by the Burdekin and Burnett Basins. In turn, crops grown in these basins are largely broad acre grains and hence the main trends in the GBRCA and Fitzroy, Burdekin and Burnett-Mary NRM regions reflect changing grain cropping in these areas. The data show that grains cropping has become an increasingly important commodity in the GBRCA, with strong growth from the 1960s (shown as ‘other crops’ in Fig. 6C) coinciding with the clearing of the Brigalow vegetation. In the Theresa Creek sub-basin of the Fitzroy Basin, grains cropping has been identified as the dominant cause of elevated erosion and contributes a higher yield per area compared to grazing lands (Hughes et al., 2010). The large annual fluctuations in the total cropping area highlight the volatility of this industry and prompted Daly (1994) to present the Queensland wheat area as a three year moving average. This analysis suggested that wheat (and likely other grain crops) perform better with seasons of above average winter rain in comparison to the livestock industry which typically perform better with above average summer rains (Daly, 1994).

Sugar cane is the dominant crop across several of the ‘wetter’ coastal basins of the Wet Tropics, Mackay Whitsunday, Burdekin and Burnett-Mary NRM regions (Fig. 8A). The different trends in the time series across these NRM regions have been influenced by several different factors which include the transition from the plantation farming system to the smaller farms with central mills farming system in the late 1800s to early 1900s (Griggs, 1997, 2000); increased clearing/draining of coastal wetland systems particularly in the Wet Tropics from the 1960s (Kemp et al., 2007); the expansion in the Herbert in the 1990s stimulated by the Sugar Industry Infrastructure Package and; the conversion of the King Ranch cattle property to sugar cane in the Tully-Murray Basin in the 1980s–1990s (Mitchell et al., 2006). The provision of water infrastructure has also greatly assisted the expansion of the sugar cane industry as observed by the growth of sugar cane area in the Haughton and Burdekin Basins during the 1990s as a result of the Burdekin Falls Dam (built 1987) and the associated development of the Burdekin-Haughton Irrigation Scheme. In addition, growth in the sugar cane area in the Mackay Whitsunday NRM region was also facilitated by the construction of the Peter Faust Dam on the Proserpine River (built 1990) and the Marian Weir (built 1952), Dumbleton Weir (built 1982; Stage 2 and 3: 1992 and 1998, respectively), Mirani Weir (built 1987) and Teemburra Dam on the Pioneer River and Kinchant Dam (built 1977; stage 2: 1986) on Sandy Creek of the Plane Basin. In contrast, the decline in sugar cane area in the Burnett-Mary NRM region is the result of a diversification of crops. This is despite the construction of the Fred Haigh Dam (1974) on the Kolan River and the Paradise Dam (2005) on the Burnett River. For a comprehensive history of the Australian sugar cane industry the reader is referred to the definitive work of Peter Griggs (2011).

The banana industry has been centred within the Tully-Murray, Johnstone, Russell Mulgrave and Barron Basins in the Wet Tropics NRM region and has been important in this region most recently since the 1980s. The early period of banana cropping in the GBRCA from 1880s to ~1917 in the Wet Tropics was largely in the Johnstone and Russell Mulgrave Basins and then further south in the Mary Basin of the Burnett-Mary NRM region from the 1910s to 1930s. Interestingly, major cyclones that have impacted the Wet Tropics such as the 1918 cyclone (made landfall in the area around Innisfail), Tropical Cyclone Winifred (1986: Innisfail), Tropical Cyclone Larry (2006: Innisfail) and Tropical Cyclone Yasi (2011: Mission Beach) appear to have had little influence on the area of bananas in the basins, although production would have almost certainly been affected.

The rapid growth in the cotton area in the GBRCA from the early 1920s was a result of the government’s desire for ‘nation building’ and the promotion of the cash crop as hardy and drought-resistant (Cook, 2019a). However, Australian cotton was grown as an annual crop due to the superior quality of cotton produced (relative to the perennial grown form) which meant it was more susceptible to drought (i.e. shorter tap roots) (Cook, 2019a) and likely explains at least some of the volatility in the annual area changes over our time series (Figs. 7 and 8C). The cotton expansion from the 1960s related to more industrial-scale production which was facilitated by the construction of water infrastructure (dams/weirs and irrigation capacity) largely within the Fitzroy NRM region (notably the Emerald Irrigation Area) (Cook, 2019a) with the Bjelke-Petersen Dam (1988) providing irrigation for a small area of cotton in the Murgon/Kingaroy Region-North district.

5.4. Translating land use to material transport – environmental gradients and management practices

Our dataset provides an important historical context for several of the current-day land use pressures on the GBRCA. Many industries such as the beef, bananas and cotton have recorded their highest annual numbers over the past decade (2010−2020) and have experienced considerable growth (> 40% increase) in the past 50 years (Table 4). In addition, population continues to rise and other industries such as mining and aquaculture all continue to add to the pressure within the GBRCA and potentially lead to issues with water quality runoff.

The land use statistics compiled here are only indirect indicators of pollution, and modelling will be required to translate land use to material transport. However, land use data can provide the means to upscale from site-specific studies that define the processes linking land use to pollution. For example, sediment source tracing and dating are powerful techniques for identifying erosion processes and spatial patterns (Collins et al., 2020). Gully and stream bank erosion have been identified as key processes that elevate sediment yields from grazing land and from past alluvial mining areas (Olley et al., 2013; Hancock et al., 2014; Bartley et al., 2018; Packett, 2020). Field studies also provide important local understanding, such as of the non-linear relationships between ground cover levels and erosion rates (e.g., Silburn et al., 2011), the processes linking grazing-induced hillslope erosion to catchment yield (Packett, 2020), and the dependence of gully erosion on stocking rate and vegetation cover (Wilkinson et al., 2018). Similarly, the amount of fertiliser applied to sugar cane strongly affects the amount of nitrogen lost per hectare in runoff (Thorburn and Wilkinson, 2013). The potential for offsite pollution clearly increases as each land use

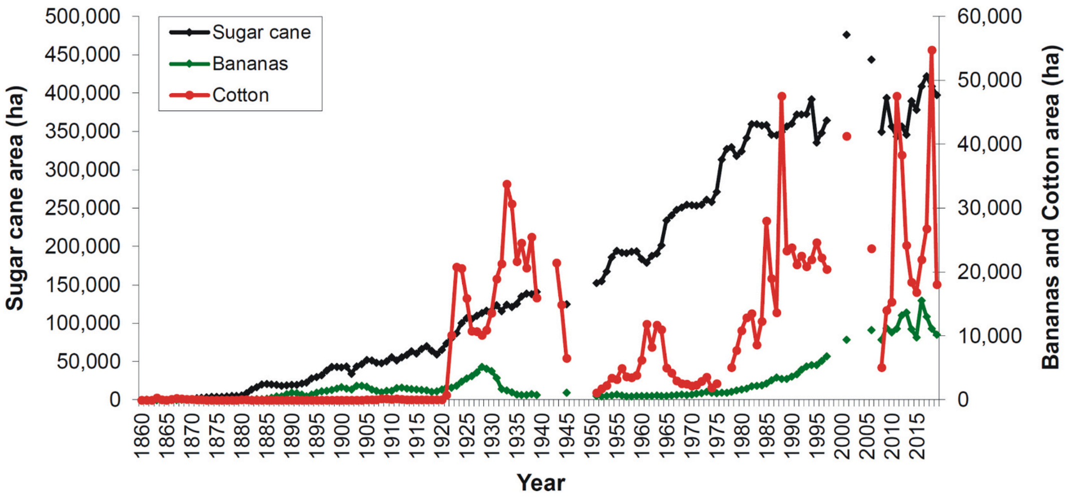


Fig. 7. Time series of sugar cane, bananas and cotton area (ha) for the Great Barrier Reef catchment area from 1860 to 2019.

becomes more intensive at a more localised scale (McKeon et al., 1990). Similarly, more intensive land uses tend to be associated with larger impacts per unit area; for example cropping tends to elevate sediment yields above those from grazing for the equivalent land area (Packett et al., 2009; Hughes et al., 2010; Thorburn et al., 2013). Based on the system understanding built from these field studies, modelling can be used to define spatial patterns in sediment sources, such as the dependence of gully erosion on rainfall, vegetation cover and terrain (Vanmaercke et al., 2020). Representing deposition within basins is also an important component in modelling the impact of land use on sediment yields (Walling, 1999; Wilkinson et al., 2014). Future studies may combine approaches outlined above with the continuous time series of land use change presented here to track the history of land use impacts on pollution. Further avenues for investigating the contributions of individual land uses are explored in the Burdekin Basin case study below.

Undoubtedly all land uses have made considerable improvements over time in management practices (e.g. Thorburn and Wilkinson, 2013) that would somewhat counterbalance the effects on erosion and nutrient losses associated with their expansion and growth over the past 160 years. For example, urban areas in the GBRCA continue to upgrade sewage treatment plants (STPs) to tertiary treatment (i.e. more targeted removal of nutrients) (33 of 129 plants in the GBRCA including Torres Strait are now at tertiary level) or consider other options such as grey water recycling to reduce their discharge to the GBR (Fearon, 2017). Water Sensitive Urban Design has also been applied across new urban developments across the GBRCA (Eberhard et al., 2017). While the dissolved inorganic nitrogen contribution from urban areas plus STPs from the GBRCA is relatively low (5.8%), this land use contributes a disproportionally higher amount given the total area (0.64%) within the GBRCA (McCloskey et al., 2021a). Improved management practices in grazing lands such as determining carrying capacity, use of forage budgets to determine stocking rates, sown pastures, weed and feral animal management, fencing and wet season spelling help maintain ground cover and reduce erosion; however the spatial extent of their effects is not well evaluated (Landsberg et al., 1998; Eberhard et al., 2017). In the sugar cane industry the introduction of green cane trash blanketing in the 1990s considerably reduced sediment export (Prove et al., 1995; Griggs, 2006) while improved management practices are being adopted to reduce nutrient and pesticide exports (Thorburn et al., 2017). Targeted extension in the banana industry has assisted in considerably reducing nitrogen fertiliser rates during the 1990s and 2000s (industry average 520 kg.ha^{-1} in the mid-1990s down to 298 kg. ha^{-1} in 1997) while improvements in fertiliser application (fertigation) and the adoption of intergrass rows are reducing nutrient and sediment exports (Daniells, 1995; DPI&F., 2007; Armour et al., 2013; Harvey et al., 2016; Eberhard et al., 2017). The cotton industry considerably reduced pesticide use in the 1990s by introducing genetically modified cotton as well as integrated pesticide management practices (Kennedy et al., 2013; Fitt et al., 2004). The grains and cotton industries have also introduced contour bank layouts and other erosion reduction mechanisms to reduce sediment exports (Owens et al., 2017; Eberhard et al., 2017). The widespread adoption of zero-till farming practices with stubble retained on the soil surface in the grain growing areas of Queensland has further reduced sediment losses. Regulations in the mining industry ensure reduced sediment erosion issues in the GBRCA compared to the now dated sluicing practices employed in historic gold and tin mining (Unger et al., 2013; Wegner, 2009), although legacy and occasional contemporary issues remain with tailings overflows of heavy metals and acidic waters (Lamb et al., 2015).

5.5. *Implications of landscape change on vegetation structure and hydrology*

Interestingly, the best available evidence suggests that there was little change in broad-scale vegetation structure in the first 100 years of pastoralism (i.e. ~ 1850–1960) as shown by Fensham (2008). In that study, broad vegetation classifications were developed using historical aerial photographs (1945–1978) and directly compared with the descriptions from the same area traversed by the explorer and naturalist Ludwig Leichhardt. The comparisons show close agreement with only a few exceptions where land had been cleared or apparent thickening had occurred (Fensham, 2008). There is still conjecture on the role of regular Aboriginal burning on shaping the landscape with some arguing that it was the dominant influence on the development of the vast open plain country (Jones, 1969; Flannery, 1994) while others suggest that rainfall variability has had greater influence on relative woody vegetation change (e.g. Fensham and Holman, 1999; Fensham et al., 2005). In some regions, regular burning of the landscape has allowed the savanna woody vegetation species largely composed of eucalypts to become dominant across large tracts of the landscape (Fensham et al., 2003). In contrast, reduced burning (including frequency and intensity of fires) since the arrival of Europeans has resulted in the expansion of rainforest at the expense of wet sclerophyll forest in parts of the Wet Tropics NRM region (Harrington and Sanderson, 1994) and *Melaleuca viridiflora* trees replacing perennial grasslands in parts of the Cape York NRM region (Crowley and Garnett, 1998; see also Fensham and Holman, 1999). An isotope-based study in the Burdekin Basin made a contrasting finding that, over the last century, vegetation thickening had occurred in 64% of sampled sites, 29% of sites had been stable while the remaining 7% of sites had thinned (Krull et al., 2007).

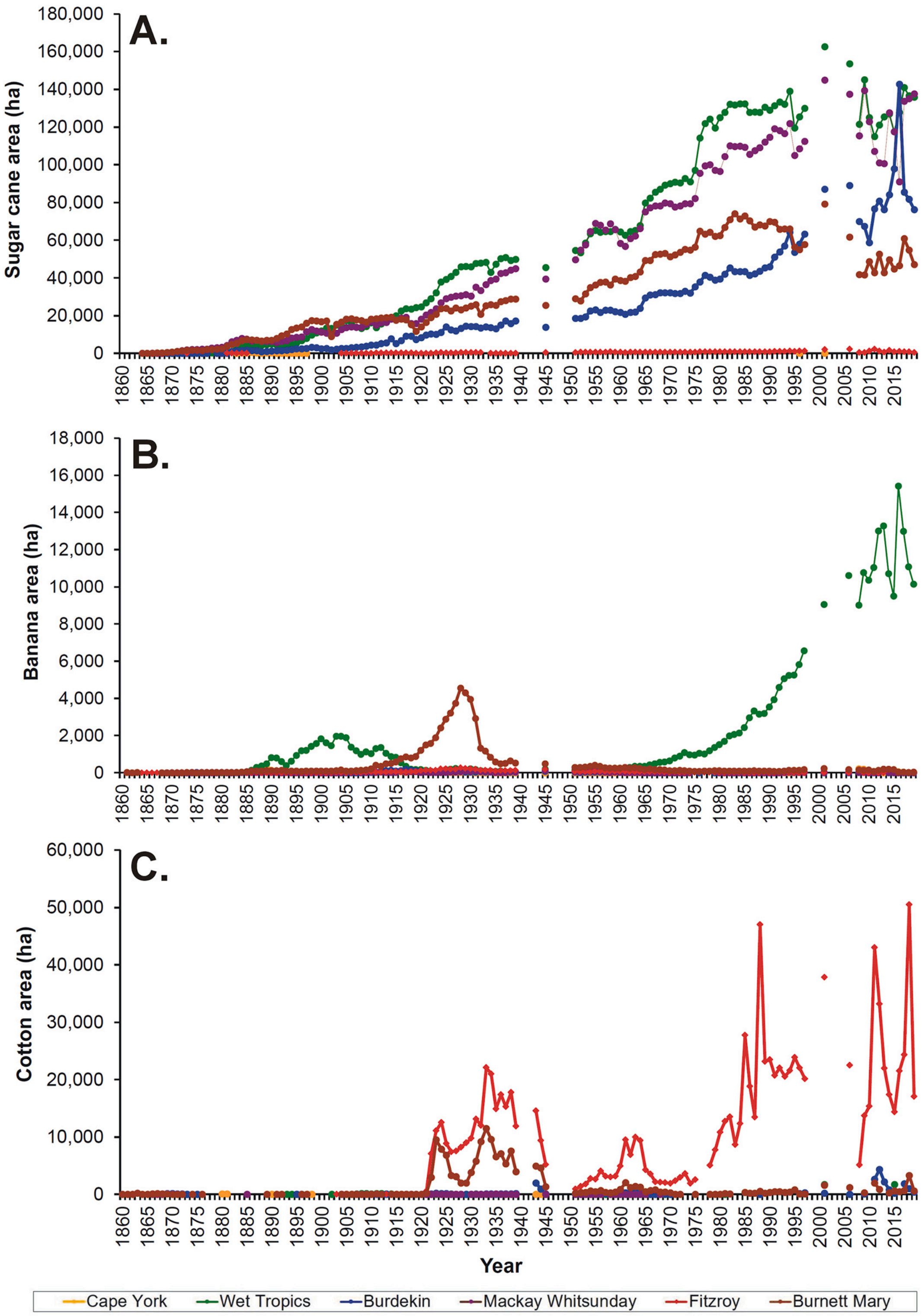


Fig. 8. Time series of area (ha) of sugar cane (A), bananas (B) and cotton (C) for the NRM regions from 1860 to 2019.

Much of the tree/shrub clearing has occurred since the ~1960s which include the government-sponsored conversion of Brigalow country to productive grazing lands (Seabrook et al., 2006, 2007) and the draining of coastal freshwater wetlands for cropping (Kemp et al., 2007). Indeed, our dataset documents the growth of the cattle industry particularly in the Fitzroy NRM region from this period (Fig. 5A, B) which also coincides with the increase in the tropical zebu cattle (*Bos indicus*) and interbreeding with the existing stock (largely *Bos taurus*) as well as the rise in the area of cropping (Fig. 6A, B) (see also Lloyd, 1984; Daly, 1994; Seabrook et al., 2006, 2007). While the clearing of the Acacia (*Acacia harpophylla*) Brigalow country down to <10% of its original distribution has resulted in increased agricultural production, it also has had negative ecological consequences including the loss of biodiversity and the potential development of dryland salinity issues (Fensham and Fairfax, 2003; Reside et al., 2017). Pollen analysis of a sediment core from Lake Nuga Nuga in the Fitzroy Basin reveal dramatic changes in the vegetation composition from the 1960s coinciding with the clearing of the Brigalow scrub (Finlayson and Kenyon, 2007). Increased grazing pressure and the introduction of exotic grasses have also resulted in a change in the composition of pasture particularly in several grazing areas across the GBRCA (McKeon et al., 2004). Along the coastal zone, the construction of State Government approved drainage schemes to remove excess water to lower the water table and reduce waterlogging of soils allowed freshwater swamps (predominantly melaleuca forests) to be drained and cleared for cropping (Griggs, 2018). The clearing of coastal vegetation systems for cropping (particularly sugar cane) has resulted in large reductions in the areas of lowland rainforest, grasslands, eucalypt woodlands and swamplands, with many vegetation types now considered rare in the GBRCA (Russell and Hales, 1993; Johnson et al., 2000; Griggs, 2007; Kemp et al., 2007).

It has been well established that the construction of water infrastructure (e.g. drainage schemes, irrigation, dams and weirs) has led to large hydrological changes of river systems across many parts of the GBRCA (Waterhouse et al., 2016). However, the modification and/or clearing of the landscape vegetation and compaction of the soils due to hard-hoofed grazing animals may have also altered the hydrological function of the landscape. For example, long term monitoring has shown that the clearing of Brigalow vegetation for either pasture or cropping has led to an increase (~ doubling) in runoff at the paddock scale (Thornton et al., 2007; Thornton and Yu, 2016; Thornton and Elledge, 2018). Initial modelling of the Comet tributary within the Fitzroy Basin supported these monitoring results (Siriwardena et al., 2006), although revised modelling of the Comet and the Upper Burdekin tributaries suggest the increase in the modelled runoff is largely attributed to rainfall variability (Peña-Arancibia et al., 2012). Cheng and Yu (2019) provide the most recent investigation by applying several models to examine the influence of the Brigalow vegetation clearing on the Comet and Dawson tributaries of the Fitzroy Basin and concluded that there has been a sizable increase in runoff due to clearing; the authors argue that the contradictions between the earlier studies relate to different methodologies and propose a multiple lines of evidence based approach. In that regard, while it has been well-established that increases in runoff due to land use changes occur at the plot (e.g. McIvor et al., 1995; Roth, 2004) and paddock (e.g. Thornton et al., 2007) scales, the examination of hydrological changes at the larger catchment scale is more difficult to quantify when coupled with climate variability (Bartley et al., 2014; Koci et al., 2020).

5.6. Burdekin Basin case study

Our annual time series compilation of land use data (population, total area under cropping, cattle and sheep numbers, gold recovered from the Charters Towers, Cape River and Ravenswood fields) can be analysed by comparisons with climate (rainfall and discharge) and with measured and reconstructed sediment loads for the Burdekin Basin to evaluate the main land use influences on biophysical changes within the Burdekin Basin and its receiving environment of the GBR lagoon (Fig. 9). Below we discuss the linkages between land use and biophysical changes at different locations:

i. Increased sediment accumulation in stream bench deposits linked to increased erosion within the catchment (Bartley et al., 2018). Bench formation has been attributed to changes in flow and flood magnitude due to changes in climate (e.g. drought) or anthropogenic activity;
ii. Changes in the rates and mercury content of coastal sedimentation (Walker and Brunskill, 1997; Lewis et al., 2014b),
iii. Changes in coral core Ba/Ca ratios and Mn concentrations that reflect increased terrestrial inputs (McCulloch et al., 2003; Lewis et al., 2007, 2018).

There are two distinct periods for increased bench accumulation in the tributaries of the upper Burdekin sub-basin which coincide with early alluvial gold mining activities and the introduction of livestock grazing (1860–1900), and later increases in cattle stocking (1950–2012) (Bartley et al., 2018). It is possible that some bench sedimentation may have occurred during the period 1900–1950, subsequently destroyed in large floods (e.g. 1946), and thus were not captured by the dating. These attributions are also generally supported by the sediment load time series, although the sediment load reconstruction also reveal elevated sediment loads in the intervening period (1900–1950), suggesting that erosion was ongoing following the initial disturbance (Fig. 9). Annual sediment loads are highly variable, indicating that the timing of sediment delivery to the coast is driven by large floods, but also that local erosion and sediment transport within the basin may display somewhat different temporal dynamics. Monitoring data show that the upper Burdekin sub basin and the Bowen-Broken-Bogie tributaries are today the dominant contributors to the sediment load exported from the Burdekin River (Bainbridge et al., 2014). Analysis of historical erosion rates using the ^{10}Be isotope show that these same tributaries have also displayed the greatest increase in erosion rates since the arrival of Europeans (Bartley et al., 2015).

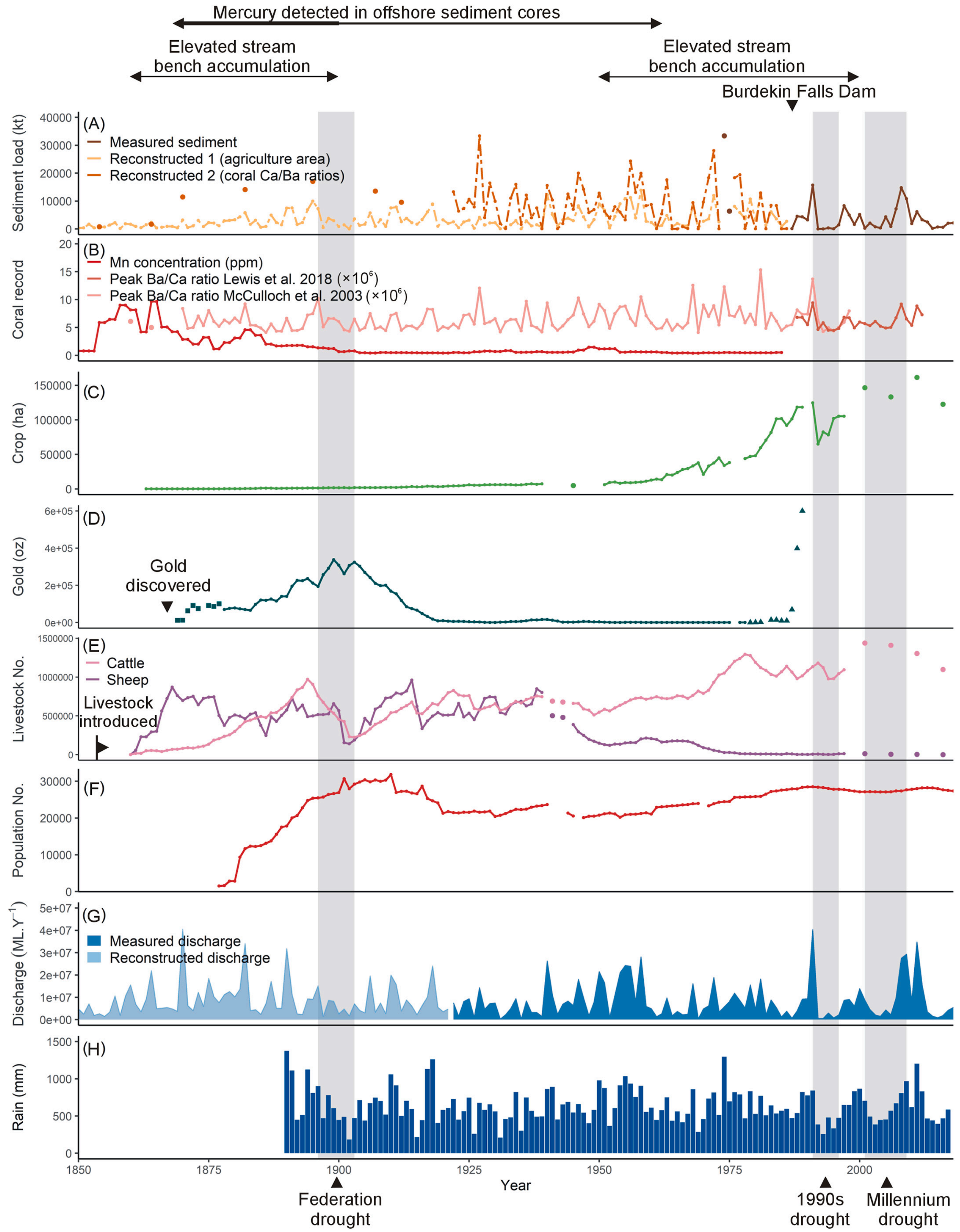
A 10-fold increase in sediment accumulation rates was measured in a marine core off the Burdekin River mouth from ~1800 CE (Lewis et al., 2014b), coinciding with the arrival of Europeans in the Burdekin Basin and the associated rise in population, livestock, mining and cropping (Fig. 9). The 1800 CE age is constrained by the limited OSL ages (two ages in the core in the past 200 years at ~1800 CE and ~ 1920 CE) and hence the specific timing of the increase in accumulation rates would be better resolved with additional ages within this section of the core.

The highest mercury concentrations in specific intervals of the marine sediment cores (Walker and Brunskill, 1997; Lewis et al., 2014b) particularly between 1868 and 1900 directly coincide with its documented use in mining activity in the Cape River, Charters Towers and Ravenswood gold fields (Fig. 9). The elevated mercury (above background concentrations) in the sediment cores continued to the 1960s and most likely reflects a legacy of its use in gold mining (Walker and Brunskill, 1997). A possible alternate explanation is the use of mercury as a fungicide in the sugar cane industry (see Walker and Brunskill, 1997; Lewis et al., 2014b). However, mercury is still widely used in the sugar cane industry (see Davis et al., 2008; Turull et al., 2018) and hence total application would likely have increased coinciding with the expansion of sugar cane area in the Burdekin Basin. Therefore, it is difficult to attribute the elevated mercury in the sediment cores to sugar cane in the Burdekin NRM region, since mercury application would then be expected to have increased coinciding with the increasing sugar cane area from the 1960s. In contrast, the mercury concentrations in the sediment cores have declined to background levels from this same time period.

Interestingly, the period of elevated coral Mn concentrations in the

Table 4
Changes in land use statistics over the past 50 years in the Great Barrier Reef catchment area.

Land use indicator	Average 1965–1969 (A)	Average 2015–2019 (B)	Factor change over the last 50 years (B/A)
Human population	511,191	1,210,415	2.37
Cattle numbers	3,832,646	5,414,977	1.41
Sheep numbers	931,209	16,639	0.02
Total cropping area (ha)	767,527	953,355	1.24
Sugarcane area (ha)	245,638	403,239	1.64
Banana area (ha)	734	11,951	16.3
Cotton area (ha)	3466	27,686	7.99
Other cropping area (ha)	517,616	510,480	0.99



(caption on next page)

Fig. 9. Burdekin Basin case study. Time series show (A) sediment load (kt) data and reconstructions (Kuhnert et al., 2012; Lewis et al., 2014a; Chaiechi et al., 2016); (B) Coral Mn and Ba/Ca records (Lewis et al., 2007, 2018; McCulloch et al., 2003); (C) annual change in total cropping area; (D) gold mining of the Charters Towers, Cape River and Ravenswood fields; (E) annual change in sheep and cattle numbers; (F) annual population change; (G) annual Burdekin River discharge (gauge and coral luminescent line data) and (H) annual rainfall (SILO data). The key drought periods are highlighted by the grey vertical bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coral core from Magnetic Island (Lewis et al., 2007) coincide with the first period of increased bench accumulation (Bartley et al., 2018) and increased gold mining activities in the Burdekin catchment including the Cape River (opened 1867), Ravenswood (opened 1869) and Charters Towers (opened 1872) fields (Fig. 9). Early photographs from the Charters Towers and Ravenswood goldfields reveal evidence for widespread areas of bare ground as the land was worked over in search of gold (i.e. one of the key early forms of mining was sluicing) (see Marsland, 1892). The specific contributions of grazing and mining to the elevated sediment loads from the Burdekin remain elusive and difficult to reconcile (for a discussion on the broader Australian context see Cook, 2019b). Grazing lands occupied a much larger area relative to mining where stock would have been concentrated near permanent water holes on streams likely promoting elevated gully and streambank erosion (Packett, 2020). On the other hand, mining would have been a more intensive land use and in some years the area of alluvial and quartz ground worked upon was considerable. For example, the 1896 statistics report that the 'extent of alluvial and quartz ground worked' was 1400 mile^2 for the Charters Towers and Cape River goldfields and 110 mile^2 for the Ravenswood goldfield (Statistics of the Colony of Queensland, 1896), although we note that while these areas were gazetted as mining fields, the actual area of mining would have likely been much smaller and largely underground (Bob Shepherd personal communication 25/10/2020). Studies in Victoria, SE Australia have demonstrated that 'sludge' derived from alluvial gold mining made a considerable contribution to sediment loads in this part of Australia (Davies et al., 2018, 2020). However, the initial increase in Mn concentrations in the coral core (1854–1856) as well as the peak concentrations in the early to mid-1860s predate mining in the Burdekin Basin and the arrival of Europeans in the Townsville region, and has been linked to the introduction of livestock in the southern Burdekin Basin (Lewis et al., 2007). Indeed, it is likely that the coral Mn record does not directly represent extensive soil erosion and increased sediment delivery but rather the loss of a repository of ash-(and Mn-)rich organic plant based surface material (accumulated by Indigenous Australian burning practices) associated with the initial introduction of livestock (see Lewis et al., 2007). Ciesiolka (1976) identified fragile erosion prone landscapes in the Burdekin Basin which included heavily grazed areas within the Upper Burdekin and the Bowen/Broken tributaries as well as associated with the Charters Towers and Ravenswood gold field areas; heavy gazing by goats surrounding the gold fields was also thought to have contributed to the erosion issues.

Annual peak Ba/Ca ratios have declined since the construction of the Burdekin Falls Dam (see also Lewis et al., 2018) and also appear to coincide with relatively lower sediment loads delivered from the Burdekin River (Fig. 9). The Burdekin Falls Dam regulates 88% of the Burdekin Basin area and traps on average 66% of the suspended sediment inflows (Lewis et al., 2013b). While the annual peak Ba/Ca ratios are correlated with measured sediment loads from the Burdekin River, there is also a correlation with annual and daily discharge and hence it is difficult to separate the sediment and discharge parameters as they are also related (see Lewis et al., 2018). In that regard, the change in the annual peak Ba/Ca ratios following the arrival of Europeans and since dam construction could be related to climate driven factors as similarly observed in the Burdekin discharge records (Lough et al., 2015) and a reduction in peak daily discharge as a result of dam regulation (see Lewis et al., 2018), respectively. Alternatively, the changes in coral Ba/Ca ratios could also reflect a change in sediment load or a combination of both discharge and sediment load. Indeed, the 5 to 10-fold increase in coral Ba/Ca ratios observed by McCulloch et al. (2003) is considerably larger than the corresponding ~2-fold increase in the coral luminescent line record (Lough et al., 2015).

The sediment load reconstructions (particularly the 'Reconstruction 2 (coral Ba/Ca ratios') are currently our best available estimates prior to the monitoring record and have been reproduced to highlight the value of a more accurate reconstruction to better assess the land use and climate drivers of sediment load (Fig. 9). Their depictions of interannual variability are likely to be more realistic than the predicted mean loads. The rare earth elements and yttrium concentrations in coral cores offer much promise for future reconstruction of the sediment load delivered directly to coral reefs (Saha et al., 2019, 2021). Associated particulate nutrients associated with the river sediment loads can be desorbed or mineralised to bioavailable dissolved forms in coastal waters and also affect the condition of coral and seagrass ecosystems (Bainbridge et al., 2012, 2018).

Sediment dating in tributaries of the Burdekin River (Bartley et al., 2018) as well as in other GBR catchments (Hughes et al., 2009; Pietsch et al., 2015) have determined that although in-channel storage of coarse sediment can be considerable in some areas, the finer (< 20 μm) sediments are generally not stored in large quantities within the channel or floodplains (Amos et al., 2009). However, this finer material can be trapped in dams (Lewis et al., 2013b) and well vegetated coastal areas (Douglas et al., 2010). Understanding the source and delivery of sediments from the various land uses requires a combination of approaches including geochemical tracing (Furuichi et al., 2016), accumulation changes in sediment cores (Douglas et al., 2010; Lewis et al., 2014b; Tibby et al., 2019) and long term land use-specific field monitoring (Bainbridge et al., 2009; Packett et al., 2009; Koci et al., 2020) to establish both the spatial and temporal impact of land use change. Improved age control resolution as well as sediment source tracing within the marine cores would also help better assign the key land use activities that relate to the increased erosion from the Burdekin Basin. In summary, the multiple sources of data suggest that in the Burdekin Basin, sediment delivery to the GBR initially increased with the introduction of livestock and mining, remained elevated with the increases in cattle and cropping, and declined slightly with the construction of the Burdekin Falls Dam.

Further modelling, supported by sediment source tracing, dating and load estimation measurement studies already undertaken, may assist to develop a deeper understanding of changes in basin runoff and sediment yield in basins such as the Burdekin, which have wide spatial and temporal variations in climate. Translating historical land use and catchment condition to vegetation cover would appear to be an important aspect of further work given the known dependence of Burdekin River sediment yield on ground cover (Kuhnert et al., 2012; Wilkinson et al., 2014).

6. Conclusions

Time series of human population and land use statistics for the period 1860–2019 have been developed from historical records for drainage basins and NRM regions in the Great Barrier Reef catchment area (GBRCA). These time series characterise the historical land use changes in the GBRCA and their possible legacy issues, to define the nature and context for the current land use pressures within the GBRCA and affecting water quality in the GBR lagoon. It is concluded that many industries such as the beef, bananas and cotton have recorded their highest annual numbers and areas since 2010. General increasing trends are observed since 1860 for human population, cattle, total area under crops, sugar cane, bananas and cotton, although different trends are evident at the finer NRM region and river basin scales. This documentation of a continuous time series of land use change at the highest possible spatial resolution across the GBRCA provides a resource which can inform the targeting and design of more detailed studies to define the land use impacts on river sediment and nutrient loads, both historical and current, as well as changes to the ecosystem condition of the receiving environment. For example, it enables investigations into the timing and causes of erosion issues at regional and basin scales, or the leaching of dissolved nutrients from cropping areas, sewage treatment plants and urban settings. This compilation presents population, livestock and cropping areas, and other industries could be added such as mining (e.g. gold, coal and tin), forestry, aquaculture and port construction. Coupling land use records with improved historical reconstructions of annual pollutant loads as well as economic drivers, will enable a more thorough analysis (e.g. Chaiechi et al., 2016) as well as to better define the biophysical changes across the catchment to reef continuum. In that regard, such foundational resources should be applied to better attribute changes in biophysical records to key climatic and land use drivers in order to establish more robust environmental histories for the GBR and elsewhere.

Data availability and copyright

All land use statistical data are provided in the Supplementary data (Excel files) at the 'as reported' district level from the annual registers. The only modification to these raw data is the conversion of the 1860–1972 cropping areas from acres to hectares. Every effort has been made to faithfully reproduce the data to ensure the number of transcription errors are minimised. The data have been derived from the annual Queensland Statistical registers (agriculture: 1860–1974) and the Australian Bureau of Statistics (agriculture: 1975–2019; human population: 1860–2019) and are copyright to the Commonwealth of Australia. The data have been reproduced under the Creative Commons Attribution 4.0 licensing.

CRediT authorship contribution statement

Stephen Lewis: Project Conceptualisation, data compilation and curation, formal analysis, funding acquisition, investigation, methodology, project administration, original draft, writing, review and editing.

Rebecca Bartley: Project Conceptualisation; funding acquisition, project administration, supervision, writing, review and editing.

Scott Wilkinson: Project Conceptualisation, writing, review and editing.

Zoe Bainbridge: Project Conceptualisation, writing, review and editing.

Anne Henderson: formal analysis, methodology, review.

Cassandra James: formal analysis, methodology, review and editing.

Scott Irvine: resources, writing, review and editing.

Jon Brodie: Project Conceptualisation; funding acquisition, supervision, review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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